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(54) **DEVICES, SYSTEMS AND METHODS FOR PASSIVE CONTROL OF FLOW**

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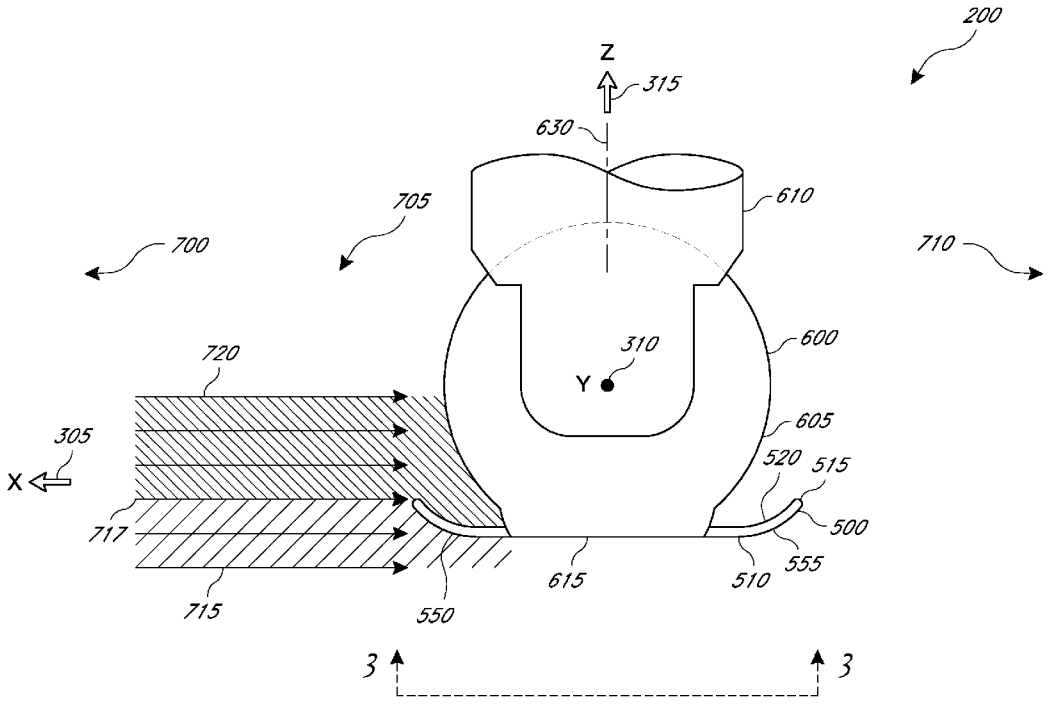
(57) **ABSTRACT**

Systems, devices and methods are disclosed for controlling the flow of a fluid over the window of an optical instrument housing in a freestream flow field. For example, the flow upstream of the housing may be split to create a flow region over the window that is conducive to successful operation of the instrument. The flow region may be maintained for various rotations of the housing about yaw, pitch, and roll axes. The disclosed features in some embodiments induce flow regions with reduced spatial and temporal density gradients of the flow over the window.



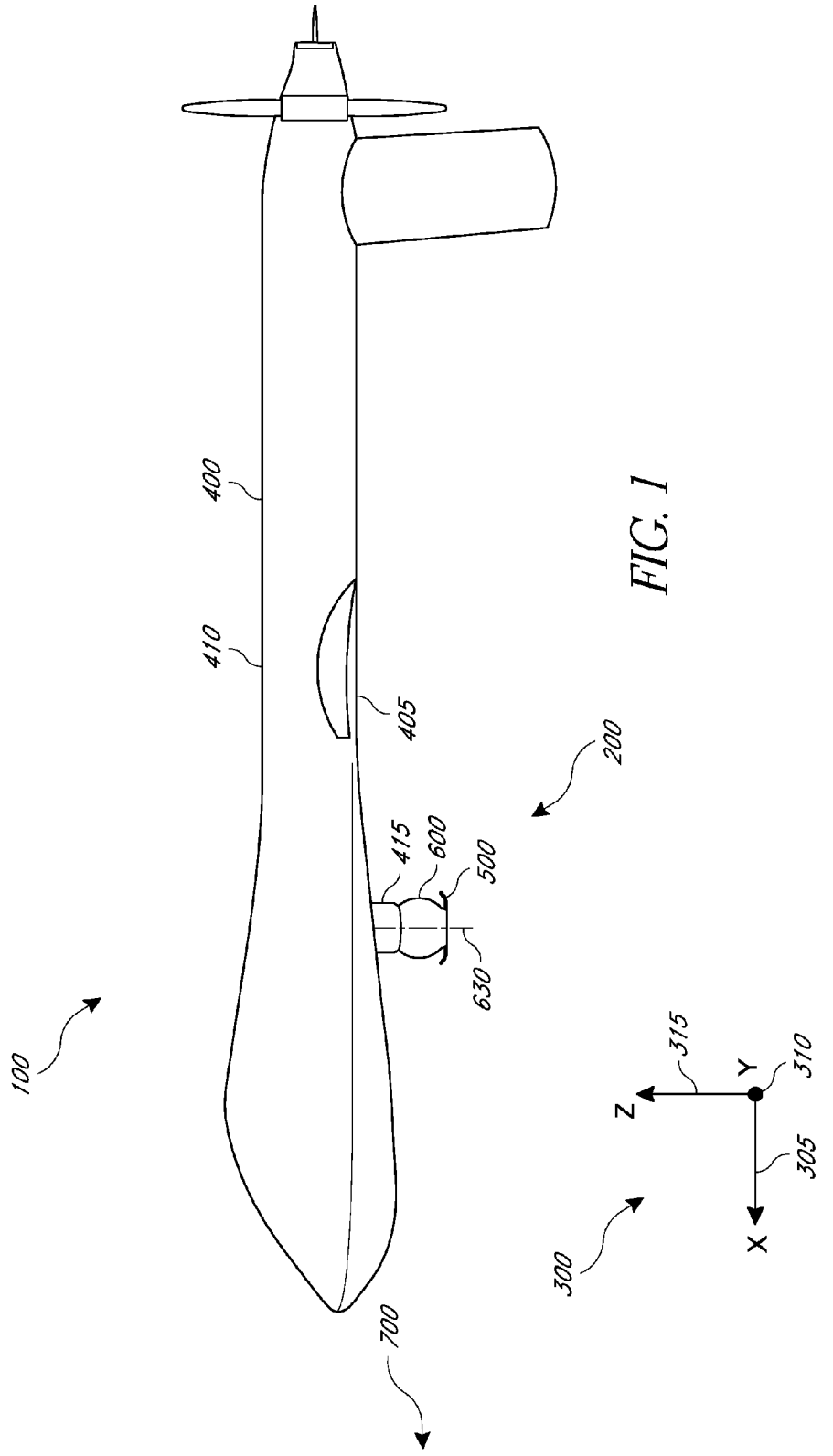


FIG. 1

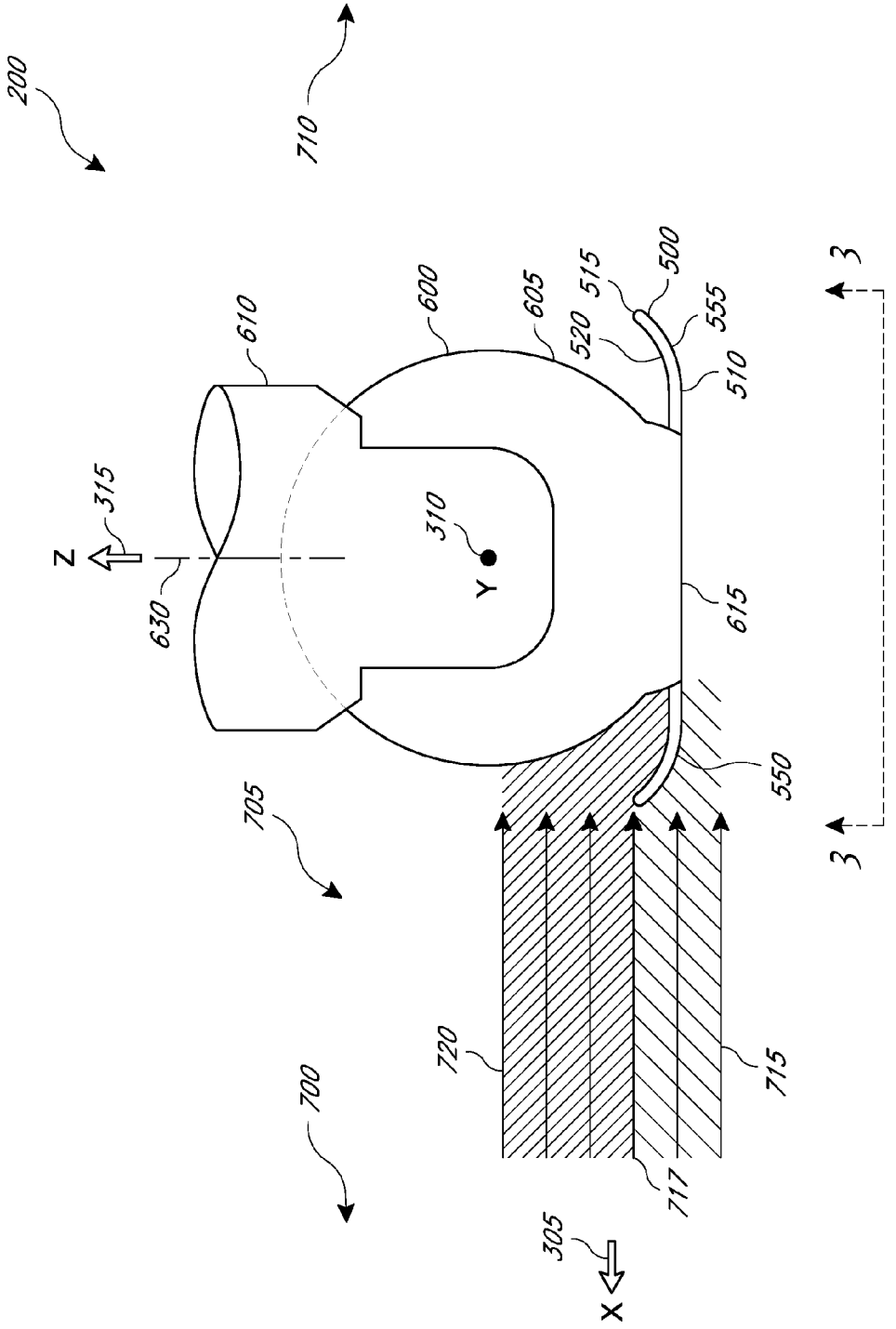

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FIG. 2

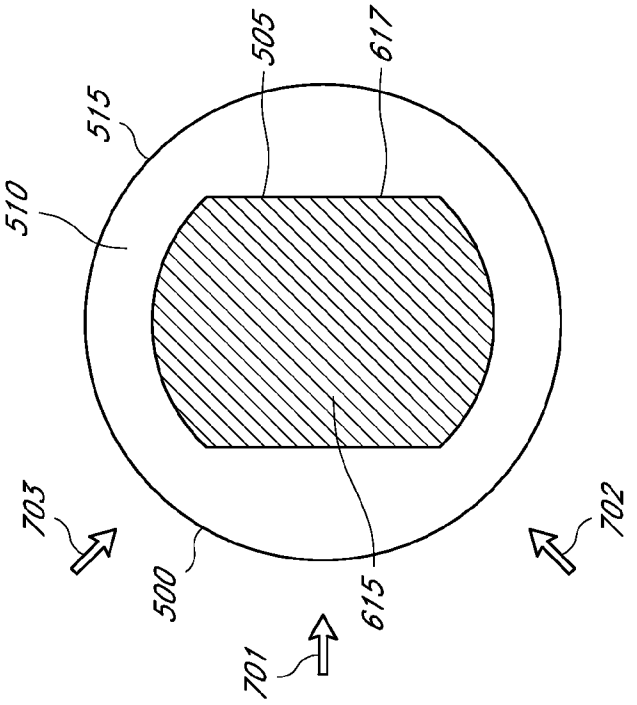
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FIG. 3B

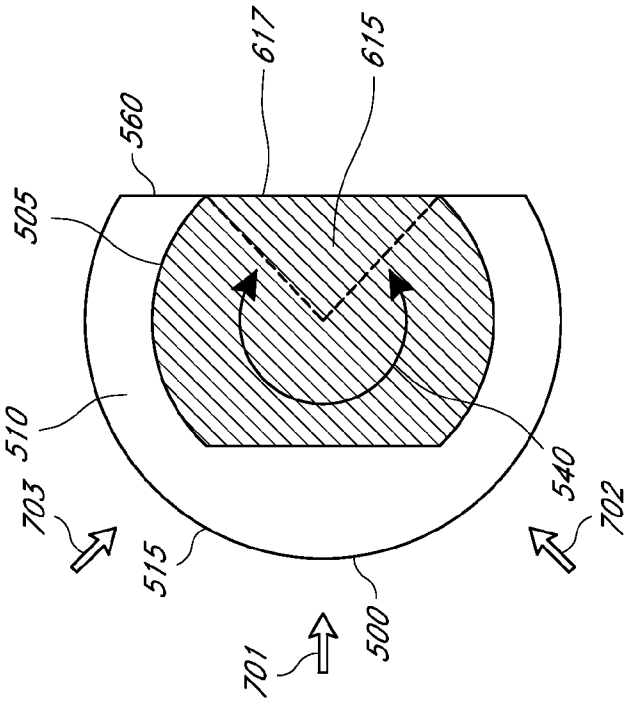
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FIG. 3A

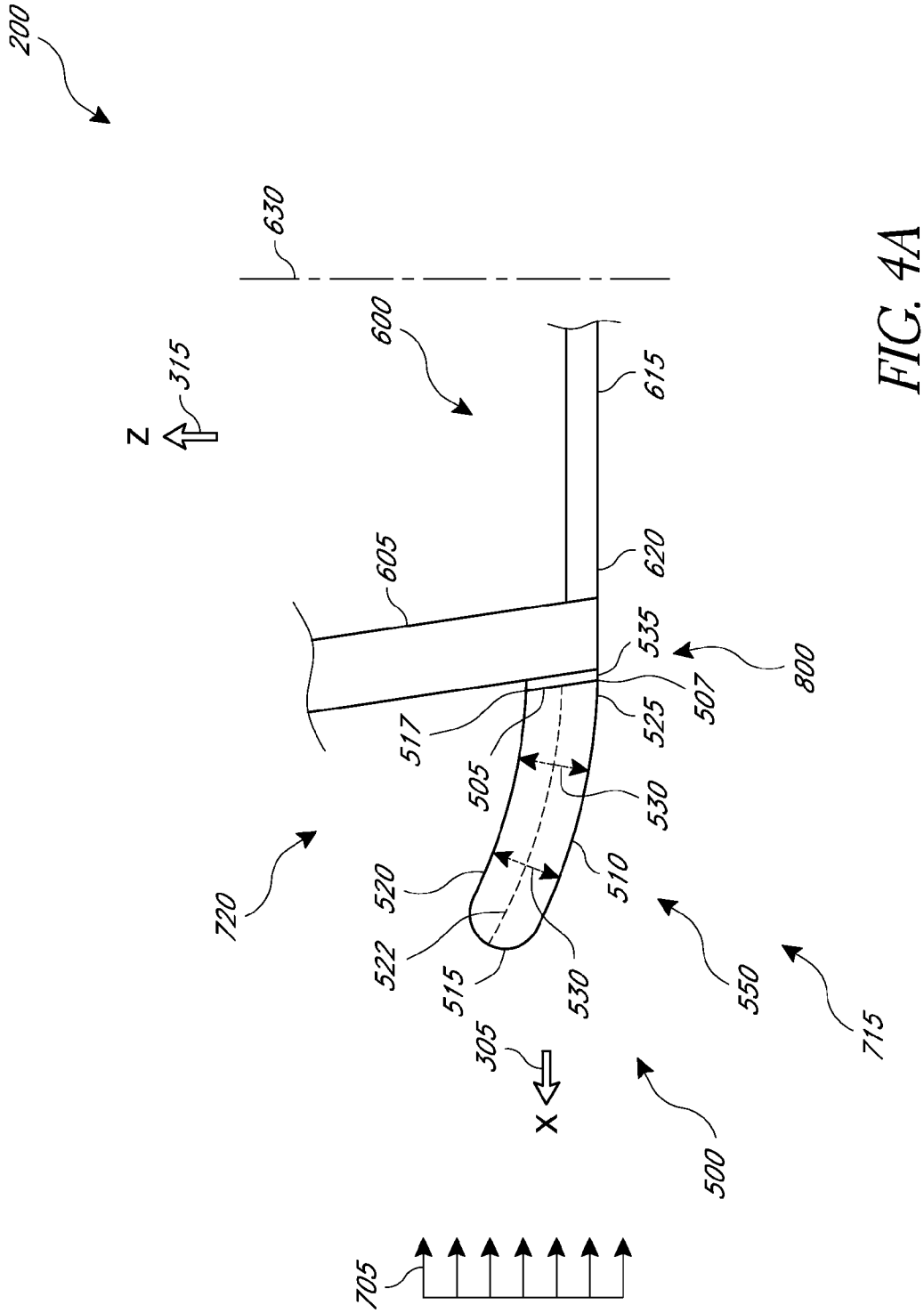
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FIG. 4A

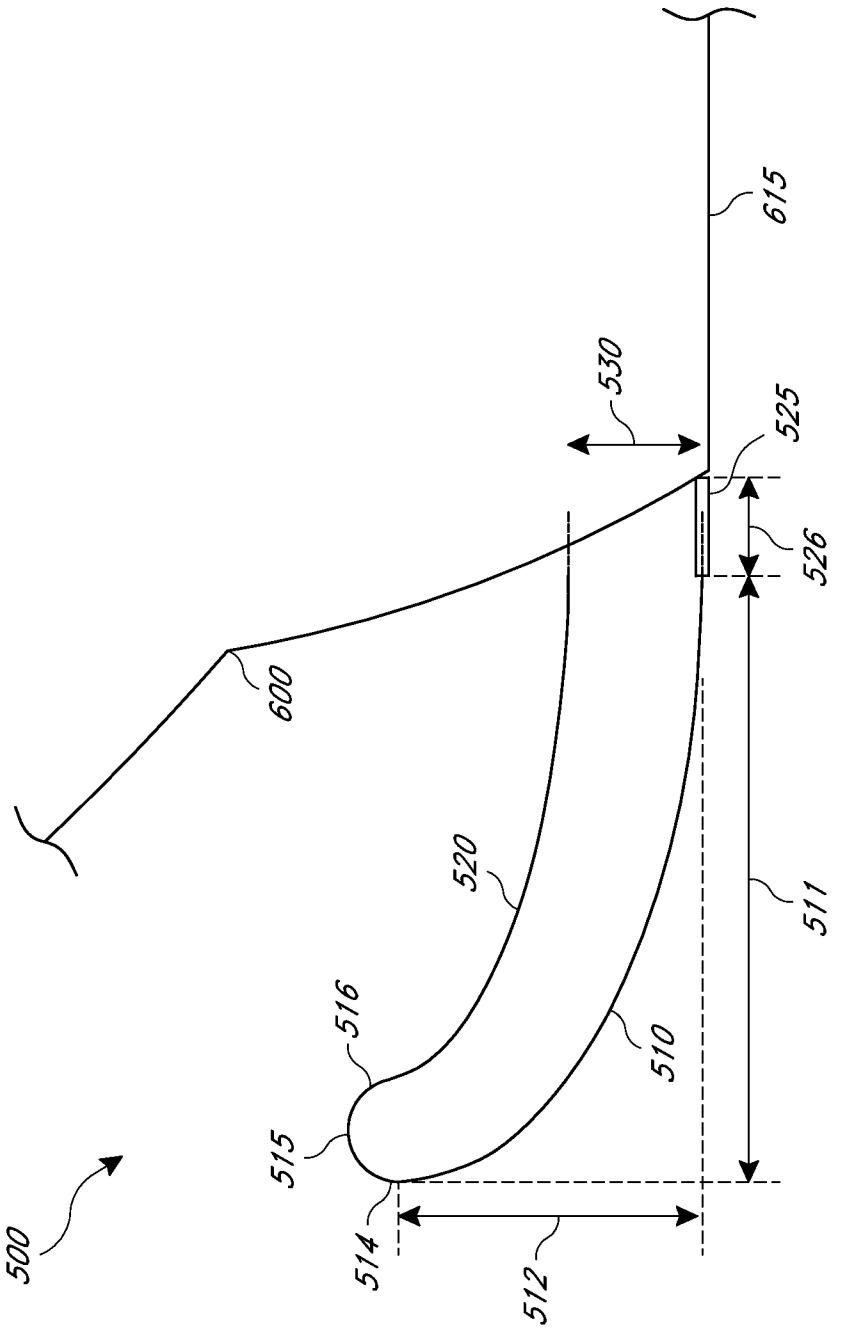

FIG. 4B

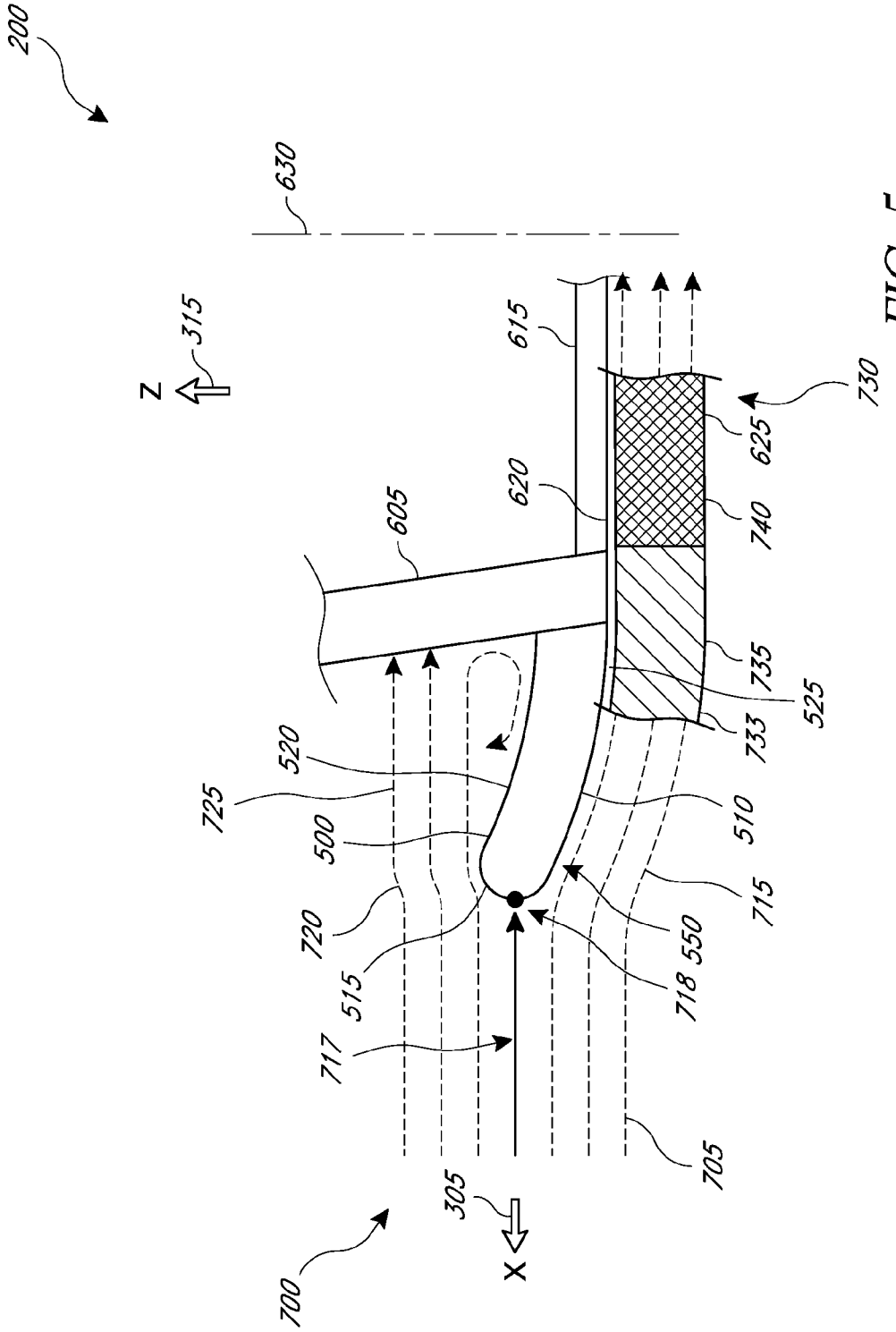
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FIG. 5

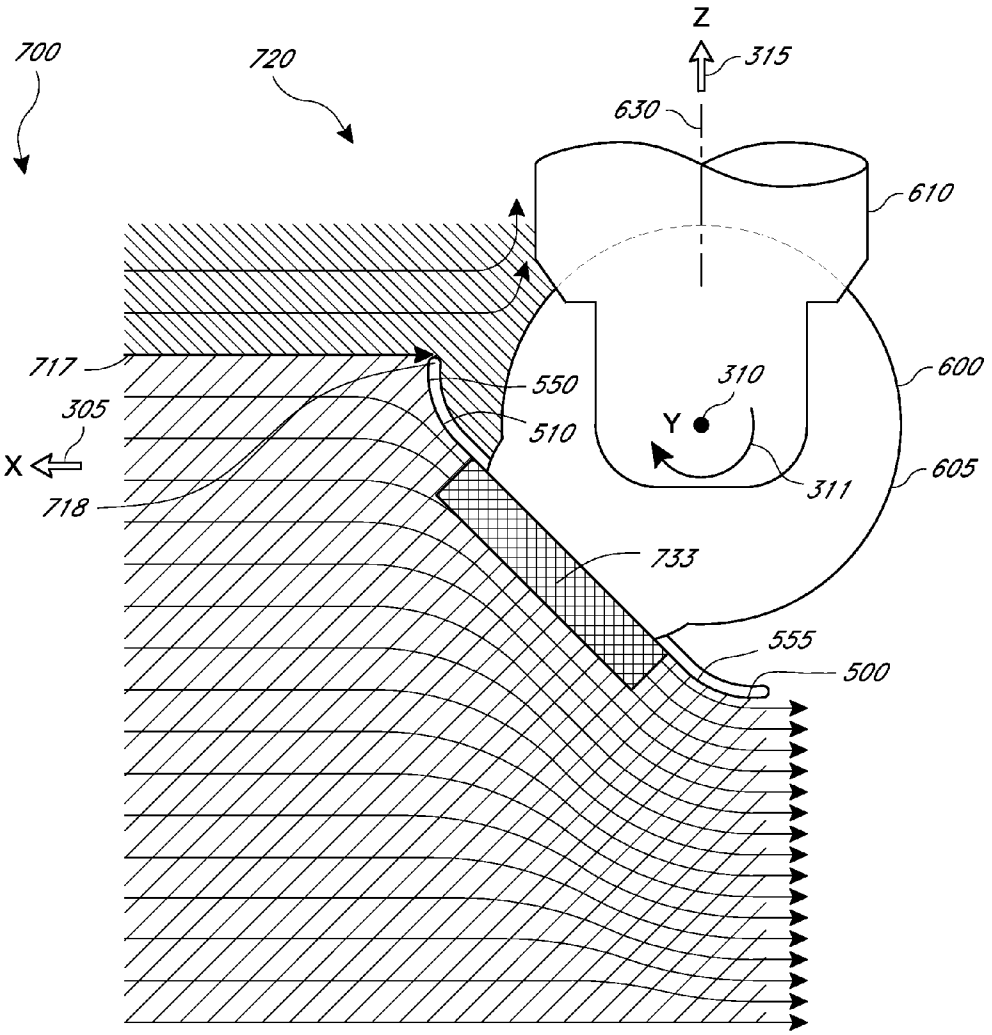
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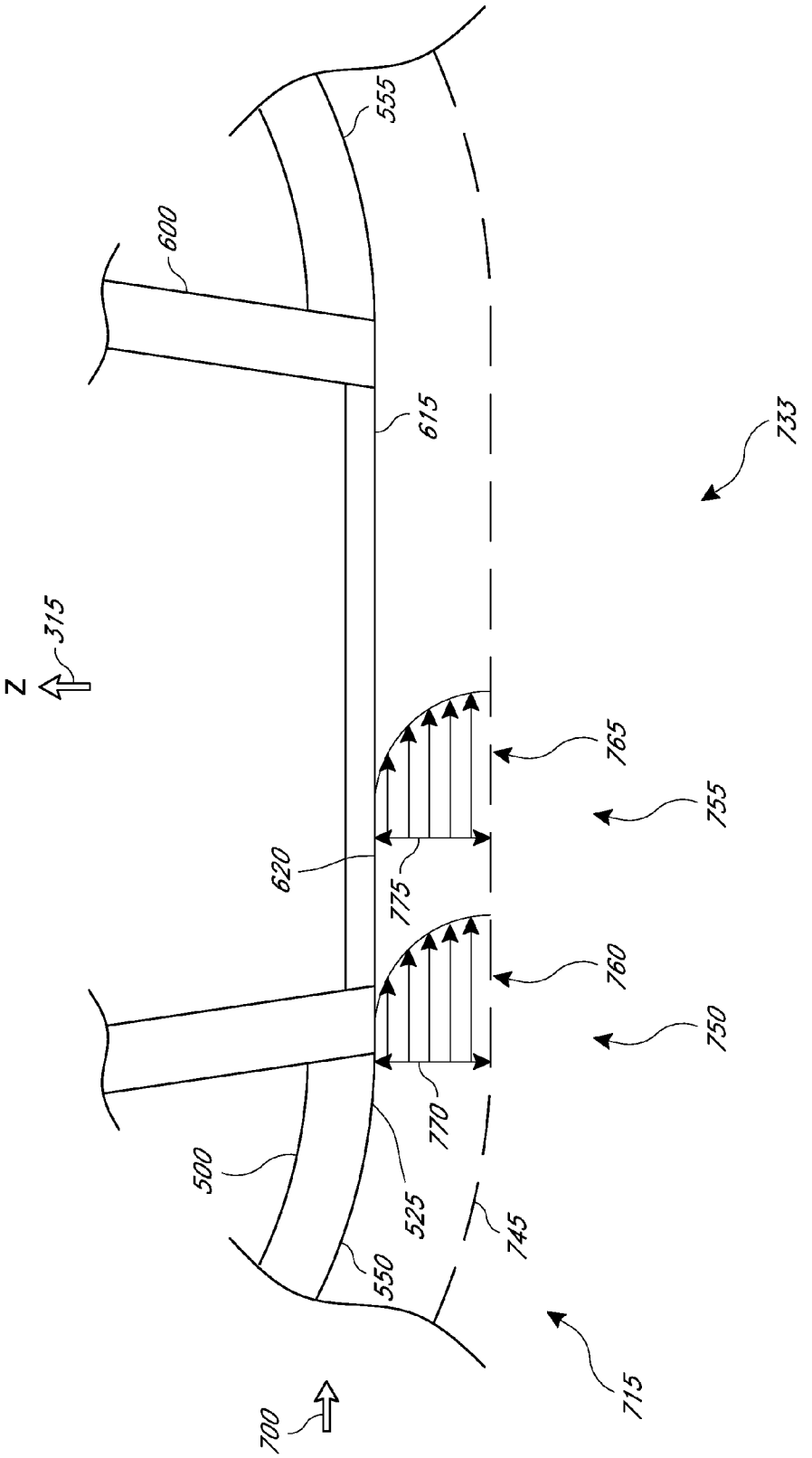
FIG. 6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745
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700

FIG. 7

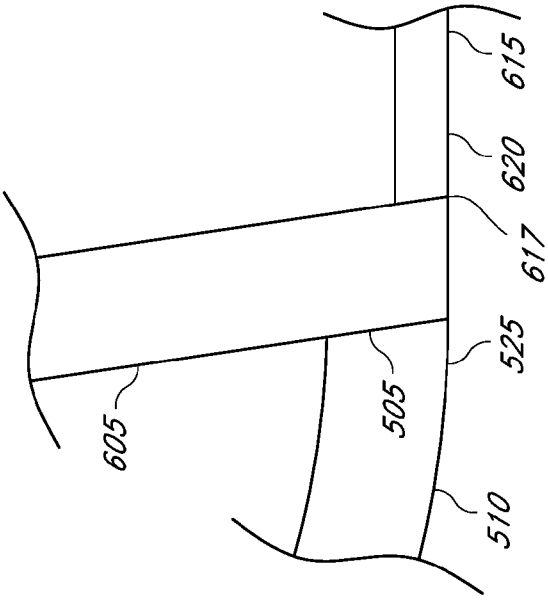
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FIG. 8B

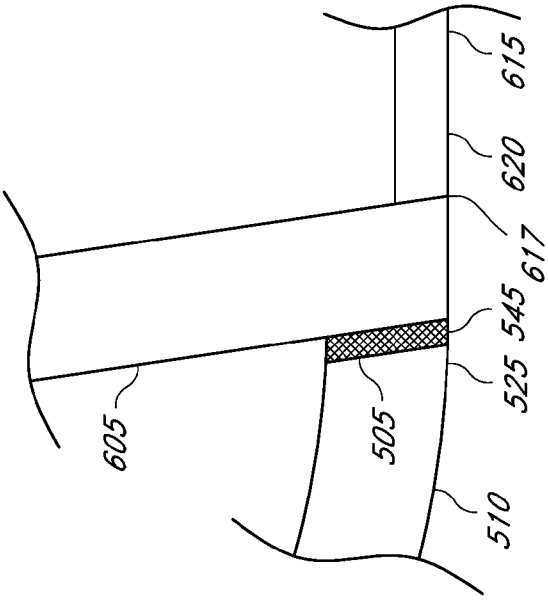
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FIG. 8A

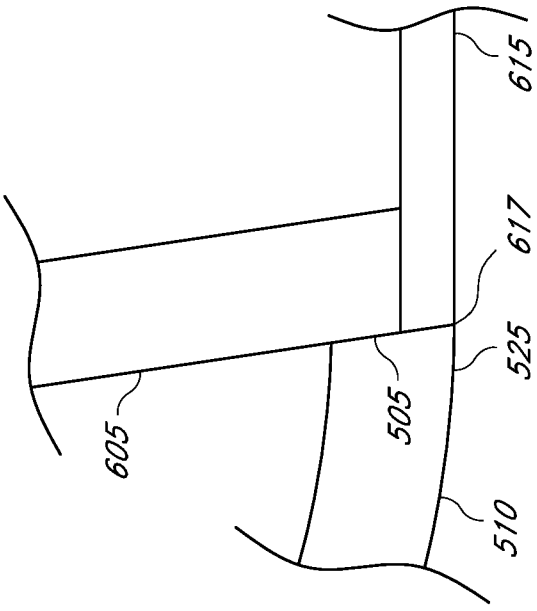

FIG. 8D

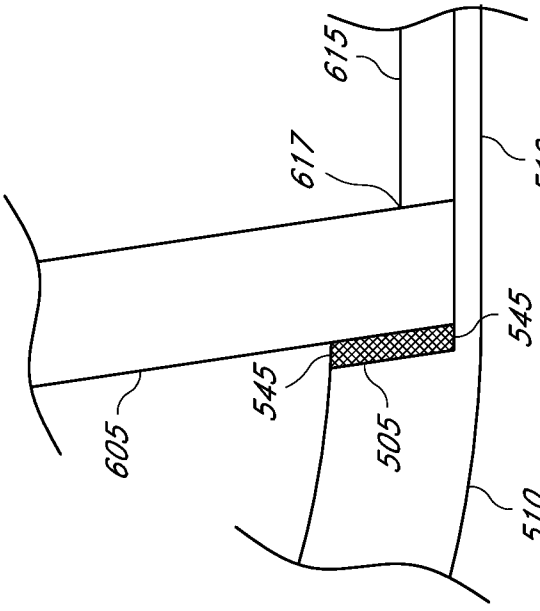

FIG. 8C

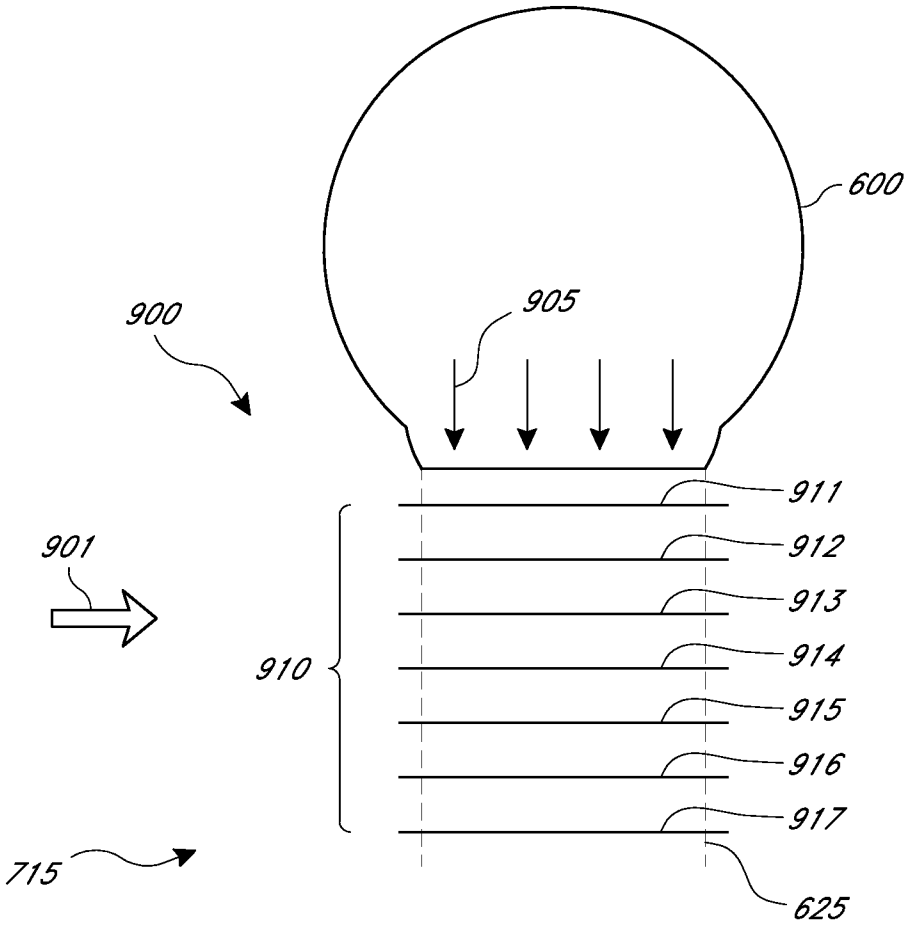

FIG. 9A

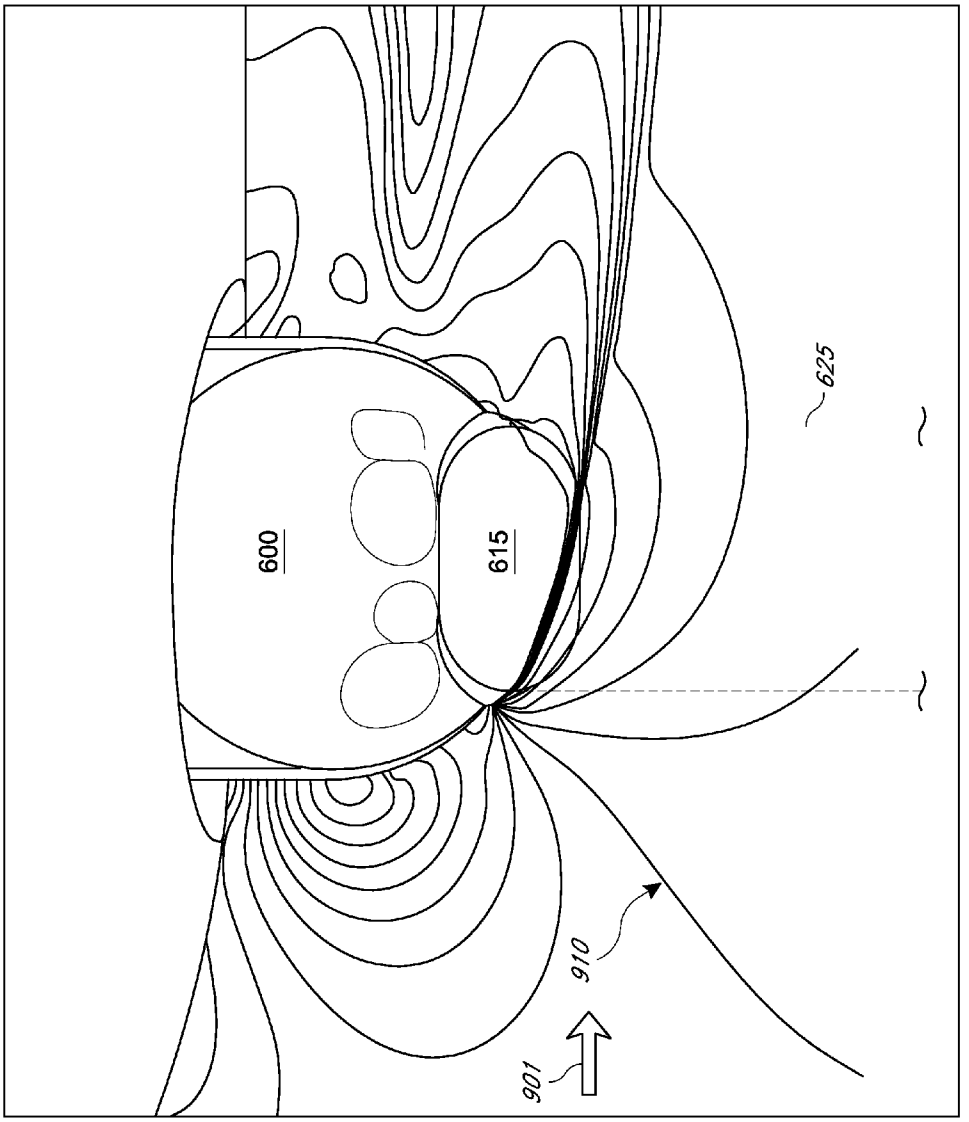

FIG. 9B

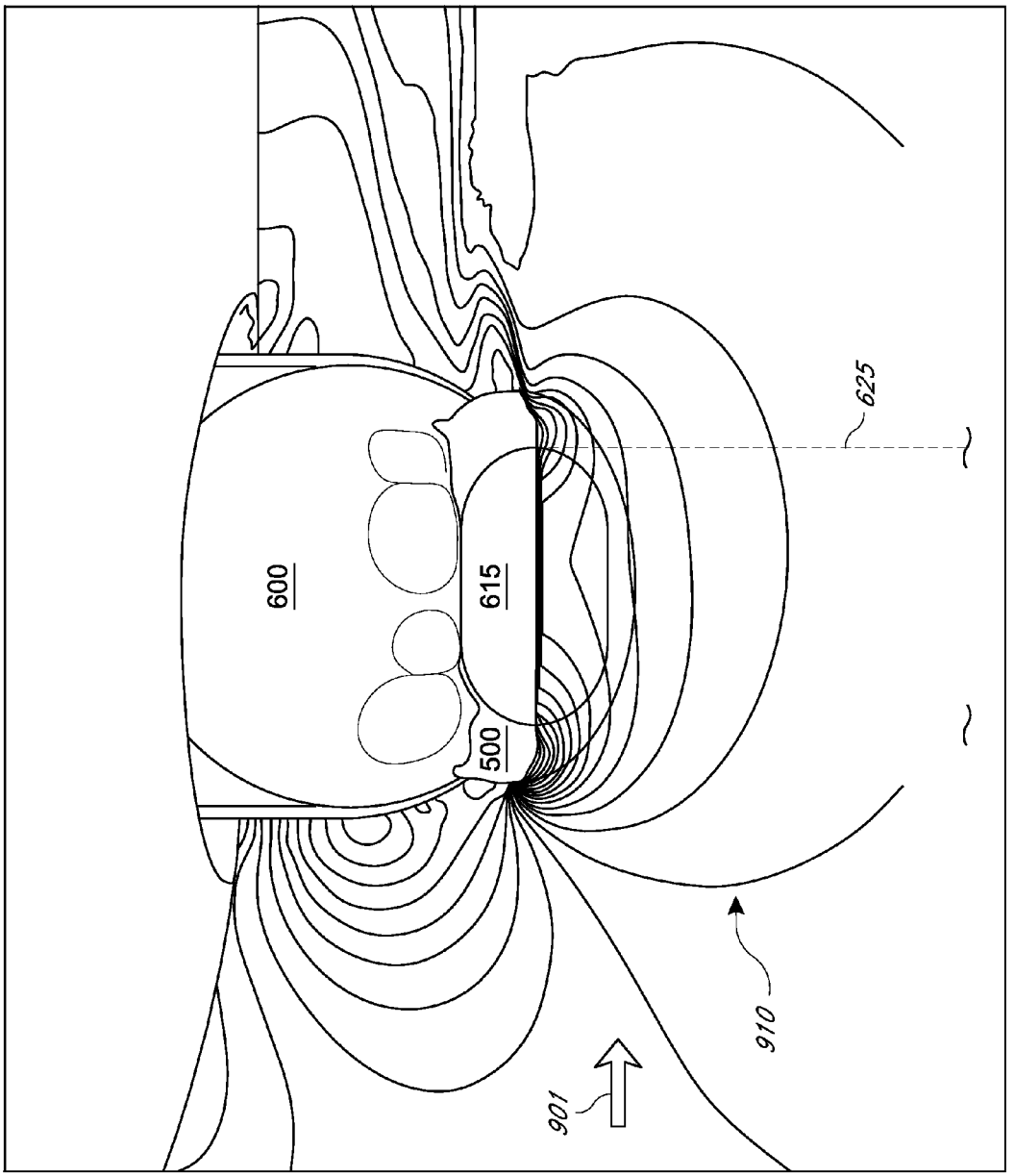

FIG. 9C

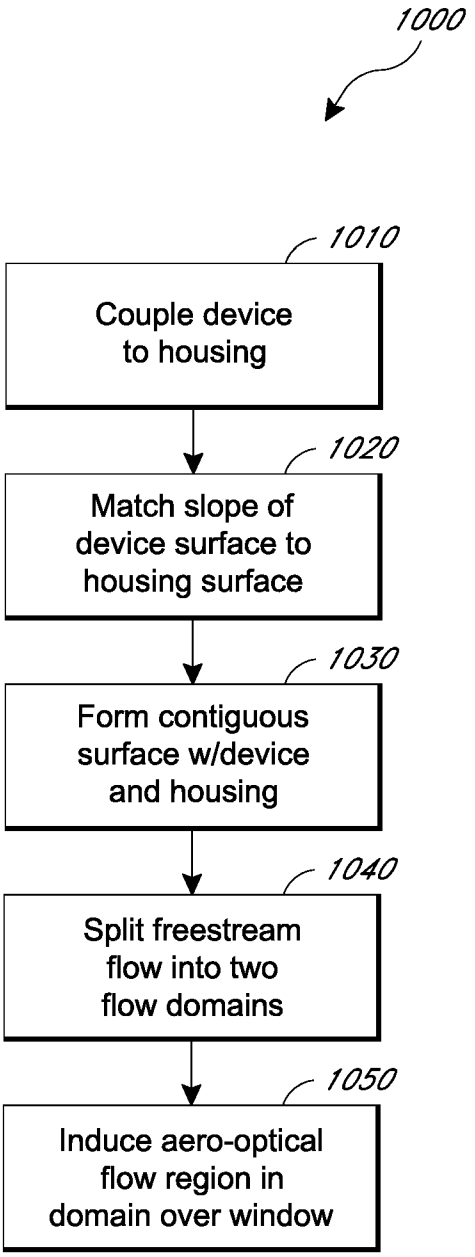
1000
1010
Couple device to housing
1020
Match slope of device surface to housing surface
1030
Form contiguous surface w/device and housing
1040
Split freestream flow into two flow domains
1050
Induce aero-optical flow region in domain over window

FIG. 10

DEVICES, SYSTEMS AND METHODS FOR PASSIVE CONTROL OF FLOW

INCORPORATION BY REFERENCE TO ANY PRIORITY APPLICATIONS

[0001] Any and all applications for which a foreign or domestic priority claim is identified in the Application Data Sheet as filed with the present application are hereby incorporated by reference under 37 CFR 1.57.

BACKGROUND

[0002] 1. Field of the Invention

[0003] This disclosure relates generally to the field of instrumentation in freestream flow fields. In particular, features for improving the flow over an optical instrument in a freestream flow field are disclosed.

[0004] 2. Description of the Related Art

[0005] Aberrations in electromagnetic energy induced by unfavorable fluid flow are a serious concern in systems that operate in flow fields. For instance, in some airborne communication and imaging systems, an optical beam is required to be transmitted through a relatively long distance, over which the quality of the beam can degrade due to variations of the index of refraction along its path. For air and many fluids, the refractive index is linearly related to the density of the fluid through the Gladstone-Dale relation, and therefore density fluctuations, such as in turbulent flow, are the root cause of these aberrations.

[0006] An electromagnetic beam in a flow field generally encounters flow in the vicinity of the instrument that is detrimental to successful operation of the instrument. For instance, turbulent flow in the vicinity of an aperture of an instrument may be produced by the presence of solid boundaries. These near-field flows typically involve turbulent boundary layers, mixing layers, and wakes. When an initially planar electromagnetic wavefront, such as an optical wavefront, passes through a flow field, different parts of the wavefront experience different densities in the medium and hence have different propagation speeds. Consequently the wavefront becomes deformed. A small initial deformation of the wavefront can lead to large errors on a distant target. The consequences of such deformations include beam deflection (bore-sight error) and jitter, beam spread, and loss of intensity. Wavefront distortions can also cause reductions of resolution, contrast, effective range, and/or sensitivity for airborne electro-optical sensors and imaging systems.

[0007] Conventional solutions addressing the problems due to such unfavorable near-field flow have included openings or channels through the vehicle or structure housing an instrument. Other approaches have involved actively influencing the flow with jets of fluid injected into the flow. Still other approaches have involved flow detection and responsive beam correction. However, these approaches are invasive, require complex sensors and systems, and/or necessitate alterations to the structure of the vehicle containing the housing. Further, these approaches limit the utility of the instruments. For instance, the orientations of the instrument with respect to the freestream flow, for which the instrument will successfully operate, are limited. As an example, approaches that employ active control with static jets of fluid limit the viewing angles of the instrument because the flow from the jets is at a different angle relative to the flow over the instrument after the instrument has rotated. While the jets themselves may move to compensate for the moving instrument, this introduces even further complexity and cost.

[0008] It is therefore desirable to address the problems associated with near-field flow over an electromagnetic instrument in a more convenient, economical, and less complex manner.

SUMMARY

[0009] The embodiments disclosed herein each have several aspects no single one of which is solely responsible for the disclosure's desirable attributes. Without limiting the scope of this disclosure, its more prominent features will now be briefly discussed. After considering this discussion, and particularly after reading the section entitled "Detailed Description" one will understand how the features of the embodiments described herein provide advantages over existing approaches to flow control.

[0010] Several embodiments are disclosed for an apparatus for controlling fluid flow over a window of a moveable optical instrument housing, the housing comprising a perimeter and at least partially protruding from a vehicle into a freestream flow field. The apparatus may comprise an inner perimeter configured to complement the perimeter of the housing, an arcuate top surface comprising a curvature and configured to extend into an upstream portion of the freestream flow field, and an arcuate outer perimeter coupled to the arcuate top surface. The apparatus is configured to couple with the housing and to split the freestream flow field into a first flow field that is at least partially above the apparatus and window and a second flow field that is at least partially under the apparatus and around the housing. The first flow field comprises an aero-optical flow region that extends at least partially over the arcuate top surface and continues at least partially over the window, and the aero-optical flow region is maintained within a range of angular orientations of the apparatus relative to the freestream flow.

[0011] In some embodiments, an inner portion of the arcuate top surface is configured to be substantially flush with an outer portion of the window when the apparatus is coupled with the housing. The inner portion of the arcuate top surface may also be configured to be substantially contiguous with an outer portion of the window when the apparatus is coupled with the housing. Further, a slope of the inner portion of the arcuate top surface may be configured to substantially match a slope of the outer portion of the window, with the outer portion of the window adjacent to the inner portion of the arcuate top surface.

[0012] In some embodiments, the apparatus is configured such that a boundary layer in the first flow field over the inner portion comprises a velocity profile substantially similar to a downstream velocity profile of the boundary layer over an outer portion of the window. The outer portion of the window may be adjacent to the inner portion of the arcuate top surface.

[0013] In some embodiments, the inner perimeter is substantially impermeable to the freestream flow field, the first flow field and the second flow field. The inner perimeter may further comprise a seal that is substantially impermeable to the freestream flow field, the first flow field and the second flow field.

[0014] The arcuate outer perimeter may be rounded and it may comprise a radius. The arcuate top surface and the outer perimeter may form a substantially smooth surface. In some embodiments, the curvature curves toward the second flow field.

[0015] In some embodiments, the apparatus further comprises a bottom surface, wherein the bottom surface and the arcuate top surface define a thickness therein. The thickness may be substantially uniform or substantially nonuniform.

[0016] In some embodiments, the inner perimeter, the arcuate top surface, the outer perimeter and the bottom surface form a plurality of cross sections of the apparatus. At least one of the cross sections may be configured to arcuately extend at least partially around the perimeter of the window, wherein at least one of the cross sections is configured to extend at least partially toward the freestream flow field. In some embodiments, at least one of the cross sections may be in a plane such that at least part of the freestream flow field in the plane is perpendicular to a line that is tangent to a point on an edge of the cross section. At least one of the cross sections may be configured to extend at least 180 degrees around the perimeter of the window.

[0017] In some embodiments, the optical instrument housing is moveable in at least two dimensions. The housing may be rotatable about a pitch axis and a yaw axis. The aero-optical flow region may be maintained for full angular rotations about the pitch, roll and yaw axes, including angular rotations of +/−180 degrees about each axis. In some embodiments, a Strehl ratio in the aero-optical flow region is at least 0.7 for electromagnetic radiation consisting of a wavelength of about 1 micrometer.

[0018] Further, the optical instrument housing may be substantially spherical and the window may be substantially planar. The optical instrument housing may comprise a turret housing on the vehicle, wherein the vehicle is an aircraft. In some embodiments, the apparatus is coupled to the turret housing.

[0019] Several embodiments are disclosed for a method for controlling fluid flow over the window of an optical instrument housing on a vehicle in a freestream flow field. The method may comprise splitting an upstream portion of the freestream flow field into a first flow field comprising an aero-optical flow region and a second flow field using an apparatus comprising an inner perimeter configured to complement a perimeter of the housing, an arcuate top surface comprising a curvature and configured to extend into the upstream portion of the freestream flow field, and an arcuate outer perimeter coupled to the arcuate top surface. The apparatus may be configured to couple with the housing, the aero-optical flow region may extend at least partially over the top surface and continue at least partially over the window, and the aero-optical flow region may be maintained over a range of angular orientations of the apparatus relative to the freestream flow.

[0020] In some embodiments, the method further comprises coupling the apparatus to the housing. Further, a substantially contiguous surface may be formed with an inner portion of the top surface and the perimeter of the housing. In some embodiments, the method further comprises matching the slope of an outer portion of the housing with the inner portion of the top surface, wherein the outer portion of the housing is adjacent to the inner portion of the top surface.

[0021] Several embodiments are also disclosed of a system for controlling fluid flow over a window of a moveable optical instrument housing that protrudes from a vehicle into a freestream flow field. In some embodiments, the system comprises a housing defining an axis and an arcuate lip comprising a curved top surface and outwardly extending away from the axis. The lip may be configured to split the freestream flow field into a first flow field above the lip and window and a second flow field under the lip and around the housing. The first flow field may comprise an aero-optical flow region that extends at least partially over the top surface of the lip and continues at least partially over the window, and the aero-optical flow region may be maintained over a range of angular orientations of the axis relative to the freestream flow.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] The foregoing and other features of the present disclosure will become more fully apparent from the following description and appended claims, taken in conjunction with the accompanying drawings. Understanding that these drawings depict only several embodiments in accordance with the disclosure and are not to be considered limiting of its scope, the disclosure will be described with additional specificity and detail through use of the accompanying drawings. In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented here. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the Figures, can be arranged, substituted, combined, and designed in a wide variety of different configurations, all of which are explicitly contemplated and make part of this disclosure.

[0023] FIG. **1** depicts a side view of an embodiment of an apparatus for control of flow over the window of an optical instrument housing mounted on an aerial vehicle.

[0024] FIG. **2** depicts a side view of the apparatus of FIG. **1** coupled to a housing and splitting a freestream flow field into two flow domains.

[0025] FIGS. **3**A-**3**B depict bottom views of different embodiments of the apparatus and window of FIG. **1**.

[0026] FIGS. **4**A-**4**B depict section views of embodiments of an upstream portion of the apparatus and window of FIG. **1**.

[0027] FIG. **5** depicts a section view of embodiments of two flow domains around the apparatus of FIG. **1**, with one of the domains containing a region of aero-optical flow.

[0028] FIG. **6** depicts a side view of the apparatus of FIG. **1** rotated about a pitch axis.

[0029] FIG. **7** depicts an embodiment of a laminar boundary layer over the apparatus and window of FIG. **1**.

[0030] FIGS. **8**A-**8**D depict various embodiments of an interface between the apparatus and housing of FIG. **1**.

[0031] FIGS. **9**A-**9**C depict various embodiments of density isolines in the flow around a housing.

[0032] FIG. **10** depicts an embodiment of a method for controlling the flow of fluid over the window of an optical instrument housing in a freestream flow field.

DETAILED DESCRIPTION

[0033] The following detailed description is directed to certain specific embodiments of the development. In this description, reference is made to the drawings wherein like parts or steps may be designated with like numerals throughout for clarity. Reference in this specification to "one embodi-

ment," "an embodiment," or "in some embodiments" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the invention. The appearances of the phrases "one embodiment," "an embodiment," or "in some embodiments" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments. Moreover, various features are described which may be exhibited by some embodiments and not by others. Similarly, various requirements are described which may be requirements for some embodiments but not others.

[0034] Some embodiments disclosed herein relate generally to systems, devices and methods of passively controlling the near-field flow over a window of an instrument housing in a flow field. The flow is controlled so that the near-field flow is more conducive to successful operation of the instrument. The flow upstream of the instrument may be split into separate domains by a device coupled with the housing. The device may interrupt the upstream flow and induce an "aero-optical" flow region, i.e. a flow region with reduced density gradients, over the window. Aberrations in the electromagnetic energy transmitted from or received by the instrument, which would be caused by distortions in the near-field flow over the housing without the device, may be mitigated. An aero-optical flow region over the window may further be induced for various orientations of the device with respect to the freestream flow field.

[0035] Some terms or phrases used herein may be unfamiliar to the reader. Therefore, descriptions of these terms will be given. The following descriptions of certain terms are meant to assist with understanding the present disclosure. The descriptions are not meant to limit the disclosure but rather clarify the meaning of these terms as they are used herein. Any examples given are merely illustrative and are not meant to limit the scope of the present disclosure. These descriptions will apply to the terms as used throughout the disclosure, unless the context in which they are used indicates otherwise.

[0036] The term "freestream flow field" is used herein in its ordinary sense as understood by those of skill in the art to refer to the far flow field that occurs when there is relative motion between a device (e.g., the device **500** or the vehicle **400** to which the device **500** is attached as depicted in FIG. **1**) and a surrounding fluid medium. In such situations, the freestream flow field is the flow that has not yet been altered or otherwise influenced by the device. The flow field **700** illustrated in FIGS. **1**, **2** and **5** is an example of a freestream flow field as described in greater detail below. As shown, it is essentially the flow field moving in the direction opposite of the direction of travel of the vehicle (and hence of the device **500**), unless there is a strong crossflow, such as a crosswind, or some other reason that the direction of flow in the surrounding environment, such as the atmosphere, would not be aligned with the direction of travel of the vehicle. In aircraft terms, the "angle of attack" would be the angle between the direction of travel of the vehicle (e.g., the vehicle **400** and the device **500**) and the free stream flow field. However, all that is required is relative motion, such that a stationary device in a moving fluid, such as an object in a blowing wind, would still be in a free stream flow field. The freestream flow field does not refer to the flow that is being altered, diverted, or otherwise influenced by the object, such as the device **500** or vehicle **400**.

[0037] The terms "aero-optical flow", "aero-optical flow region" and similar terms are used herein to refer to near-field fluid flow that is conducive to successful propagation of electromagnetic energy beams through the fluid flow. Such beams include, but are not limited to, optical beams. Aero-optical flow has improved, i.e. reduced spatial and/or temporal density gradients, in the near-field fluid flow in planes that are substantially perpendicular to the direction of propagation of the beam. The aero-optical flow density gradients are reduced relative to what the density gradients in the near-field flow over the housing would be without the use of the device. "Near-field" is used herein in its ordinary sense as understood by those of skill in the art to refer to the region of turbulent flow in the vicinity of an object without the device (such as a housing **600** without the device **500**), produced by the presence of solid boundaries, such as the boundaries of a physical housing. Therefore, the flow in an aero-optical flow region will have reduced gradients, or differences, in space and over time in the near-field flow in the aforementioned planes compared to, for example, more turbulent and/or separated flow. The aero-optical flow region thus may be a laminar flow region, which refers to fluid flow in smooth layers with minimal disruption between the layers. Thus, for example, the aero-optical flow region may be a laminar flow region and can be represented by generally parallel lines as illustrated in FIG. **5** in the first flow domain **715**. However, the aero-optical flow need not be laminar flow. As described in greater detail below, aero-optical flow includes flow across an optical window that allows for an improved optical field of view as compared to more turbulent and/or separated flow. Thus, for example, the flow region **733** over the optical window **615** illustrated in FIG. **5** can provide improved image quality as compared to turbulent and/or separated flow even when the flow region **733** is not perfectly or substantially laminar. Those skilled in the art will understand that if a device such as the device **500** is oriented at an angle to the direction of the free stream flow field **700**, the portion of the flow field **705** over the device **500** may not be perfectly or substantially laminar over the device **500** and the optical window **615**, but the flow may nonetheless be sufficiently aero-optical for the instruments to perform at an improved level as compared to the performance without the device **500**. This may include sufficiency for achieving a certain desired Strehl ratio. Thus, the portion of the flow field **705** in these situations over the device **500** would be considered "aero-optical flow" for the purposes of this disclosure.

[0038] The term "optical instrument" is used herein in its ordinary sense as understood by those of skill in the art to refer to sensors or other devices which may benefit from the improved near-field aero-optical flow. Therefore, an optical instrument may refer to an optical transmitter and/or receiver, as well as other devices configured to receive and/or transmit various forms of electromagnetic energy, such as optical, visual, infrared (IR), near IR, thermal IR, microwave, etc. The instrument may include, but is not limited to, passive sensors, active sensors, imaging sensors, microwave radiometers, synthetic aperture radar (SAR), inverse synthetic aperture radar (ISAR), meteorological radar, forward looking IR, etc.

[0039] The term "arcuate" is used herein in its ordinary sense as understood by those of skill in the art to refer to an arc or curved shape of an object or device when viewed from a particular vantage point, e.g., the top or bottom. For example, the arcuate top surface **510** of the device **500** forms an arc as illustrated in FIGS. **3**A-**3**B and described in greater detail below. "Arcuate" thus includes any arc or curved shape,

whether simple or complex, e.g., circular, elliptical, a combination, or some other curved shape defining the path that a cross-section of the device sweeps out.

[0040] The term "inner perimeter" is used herein in its ordinary sense as understood by those of skill in the art to refer to an inner surface (or portion thereof) of an object or device. For example, in the context of FIGS. **3**A-B, the inner perimeter **505** refers to the portion of the device **500** that is closest to a window **615** when installed on a housing **605**, as described in greater detail below. Thus, an inner perimeter of a device may be an edge, sharp or rounded, have holes for attachment, or any other geometry needed for the inner portion of the device to fit onto or mate with the housing or an adapter on the housing.

[0041] The term "complement" is used herein in its ordinary sense as understood by those of skill in the art to refer to the mating or fitting of one device or object to another. For example, in the context of FIGS. **3**A-B, the inner perimeter **505** is configured to fit (and thus complement) the perimeter of the housing **600**, which may be the window **615**, as described in greater detail below. Thus, "complement" refers to such a fitting. For example, if an outer part of a housing is rounded and another part is flat, then a device that complements such a housing will have a partially rounded and a partially flat inner perimeter, in order to fit such a shape of the housing. The term "complement" includes this fitting and any other geometry to which the device is configured to fit, including geometry of an adapter.

[0042] The term "substantially flush" is used herein in its ordinary sense as understood by those of skill in the art to refer to configurations in which two surfaces are coplanar or nearly coplanar where they meet together to form an interface (e.g., the interface **800** in FIGS. **8**A-**8**D). For example, FIG. **8**A illustrate configurations in which a top surface **525** of the device **500** is substantially flush with an outer portion **620** of the window **615**. Those skilled in the art will understand that the term "substantially flush" includes configurations in which the surfaces are exactly coplanar, as well as nearly coplanar configurations that still produce the desired aero-optical flow region **733** over the window **615**.

[0043] The term "substantially contiguous" is used herein in its ordinary sense as understood by those of skill in the art to refer to configurations in which two or more surfaces together form an uninterrupted surface or a surface with only a very small gap, or gaps, that do not disturb flow across the two or more surfaces. For example, "substantially contiguous" includes configurations such as those illustrated in FIG. **4**A in which an outer surface of structures **525**, **535**, **605** and **620** together form an uninterrupted surface as discussed in greater detail below.

[0044] The term "range of angular orientations" and similar terms are used herein in their ordinary sense as understood by those of skill in the art to refer to the orientation of a device with respect to the direction of a free stream flow field. For example, as illustrated in FIG. **1** and discussed in greater detail below, the device **500** is attached to moveable optical instrument housing **600**, both of which can be rotated about a pitch axis (elevation angle), and/or a yaw axis (azimuth angle), and/or a roll axis (roll angle), including combinations thereof. The term "range of angular orientations" includes any of these rotations, alone or in combination.

[0045] FIG. **1** depicts an embodiment of a flow control system **100** including a flow control subsystem **200** on a vehicle **400** in a freestream flow field **700**. The vehicle **400** may include a top side **410** and a bottom side **405**. A side view is shown of an embodiment of the flow control subsystem **200** coupled to the bottom side **405** of the vehicle **400**. In some embodiments, the vehicle **400** is an aerial vehicle, such as an aircraft as shown in FIG. **1**. However, the type of vehicle is not critical. For example, in some embodiments, the vehicle **400** may be an unmanned aerial vehicle (UAV), a drone, a remote control flying craft, a missile, a helicopter, or any other airborne structure in the freestream flow field **700**. The vehicle **400** may further be a static or stationary structure in a moving fluid medium. In some embodiments, the vehicle **400** may be a tower or building in a windy atmosphere. The vehicle **400** may also be vehicles or structures that operate in or otherwise contact fluid mediums other than air. In some embodiments, the vehicle **400** may be an underwater vehicle, such as a submarine, submergible, or remotely operated underwater vehicle (ROV). Other scenarios where there is relative motion between the flow control subsystem **200** and the freestream flow field **700**, although not explicitly addressed herein, are within the scope of the present disclosure.

[0046] For reference, FIG. **1** also shows an axis system **300**. The axis system **300** includes a roll axis or X axis **305**, a pitch axis or Y axis **310**, and a yaw axis or Z axis **315**. Positive directions for the X axis **305** and Z axis **315** are indicated by the arrows on the respective axes as shown. The positive direction for the Y axis **310** is out of the plane of the paper, or in accordance with the right hand rule. Angular rotations about the three axes **305**, **310**, **315** are about angles that are herein referred to as a roll angle **306**, an elevation angle **311**, and an azimuth angle **316**, respectively. In some embodiments, the axis system **300** is defined relative to the vehicle **400**. For instance, in some embodiments the vehicle **400** is an aerial vehicle with the +X direction in the direction of the nose of the aircraft, the +Y direction roughly in the direction of the left wing, and the +Z direction defined according to the right-hand rule, i.e. vertically up as shown. In some embodiments, the freestream flow field **700** is in the −X direction, as shown. In some embodiments, the top side **410** of the vehicle **400** is on the +Z side of the vehicle **400** and the bottom side **405** is on the −Z side. Therefore, unless otherwise stated or implied by context, the orientations referred to herein relating to the X, Y, and Z directions are as shown in FIG. **1**.

[0047] In some embodiments, the flow control subsystem **200** includes a housing **600** with a device **500** for controlling fluid flow over the housing **600**. The subsystem **200** may be integral with the vehicle **400** or coupled to the vehicle **400** by structurally mounting the subsystem **200** directly to the vehicle **400**. The subsystem **200** may be rigidly attached, mounted, connected, etc. to the vehicle **400** with screws, rivets, fasteners, etc. In some embodiments, an attachment **415**, such as a mounting structure or other in-between structure, is between the subsystem **200** and the vehicle **400**. In some embodiments, the attachment **415** is a modular connection structure attached to or integral with the vehicle **400** such that many different subsystems **200** may be connected to and disconnected from the vehicle **400** via the attachment **415**. In some embodiments, the flow control subsystem **200** is coupled to the bottom side **405** of the vehicle **400**. In other embodiments, the flow control subsystem **200** is coupled to the top side **410**. In some embodiments, the flow control subsystem **200** is coupled to the vehicle **400** via the housing **600**, as shown. In some embodiments, the housing **600** is mounted to the bottom side **405** of the vehicle **400**. In some embodiments, the housing **600** is mounted to the bottom side

405 directly, via an in-between structure, or combinations thereof. Other configurations and positions for the subsystem 200 and the vehicle 400, although not explicitly addressed herein, are within the scope of the present disclosure.

[0048] In some embodiments, the housing 600 is a generally symmetric structure, as shown. The housing 600 may be spherical, cylindrical, or any other shape. The housing 600 may also be asymmetric. The housing 600 may possess some symmetric features and some asymmetric features. In some embodiments, the housing 600 is a turret.

[0049] In some embodiments, the housing 600 protrudes from the vehicle 400 into the freestream flow field 700. As shown, the housing 600 may protrude into the freestream flow field 700 that is on the −Z side of the vehicle 400. In some embodiments, the housing 600 may protrude into the freestream flow field 700 that is on any side of the vehicle 400, including the +Z side, the +/−Y side, the +/−X side, and/or any positions therebetween.

[0050] As shown, the housing may define a housing axis 630. The axis 630 may be coincident with the Z axis 315. The axis 630 may move with the housing 600 as the housing 600 moves, such that the axis 630 is not always coincident with the Z axis 315. In some embodiments, the axis 630 indicates a line of sight of electromagnetic energy that is being received and/or transmitted by an optical instrument in the housing 600. In some embodiments, the electromagnetic energy is parallel or substantially parallel with the axis 630.

[0051] In some embodiments, the device 500 is located on a far end of the housing 600 that is farthest from the vehicle 400, as shown in FIG. 1. In some embodiments, the device 500 is located at other locations or positions of the housing 600, such as near the far end of the housing 600, on the side of the housing 600, on a location of the housing 600 that is closer to the vehicle 400, etc. Any other location of the device 500 is contemplated where the device 500 may influence flow from the freestream flow field 700 over the housing 600. In some embodiments, the housing 600 is integral with the vehicle 400 and the device 500 couples to the vehicle 400 at the integral housing 600. For instance, the housing 600 may be a protrusion in the fuselage structure of an aerial vehicle and the device 500 may couple to the protrusion, either directly or via an interface 800. In some embodiments, the housing 600 is pointed in the −Z direction, as shown. This may be a natural or typical orientation and/or position of the housing 600, such that rotations or movements of the housing 600 are with respect to this orientation and/or position.

[0052] FIG. 2 depicts a side view of an embodiment of the flow control subsystem 200 in the freestream flow field 700. In some embodiments, the flow control subsystem 200 includes a flow control device 500 and the instrument housing 600. For clarity, the housing 600 and device 500 are shown separate from the vehicle 400. In some embodiments, the housing 600 is an instrument housing with a window 615. The housing 600 may be a single part or it may contain a number of parts. As shown, the housing 600 may include a stationary or static structure 610, a moveable structure 605, and the window 615. The static structure 610 may be integral with the vehicle 400 or it may be rigidly coupled to the vehicle 400. The moveable structure 605 may be rotatably coupled with the static structure 610 such that the moveable structure 605 may rotate or otherwise move relative to the static structure 610.

[0053] In some embodiments, the window 615 is at least partially transparent to electromagnetic energy, such as energy in the IR and/or visual band of the electromagnetic spectrum. The window 615 may be any number of materials, including a glass such that the material is an amorphous or non-crystalline solid material that exhibits a glass transition. Such materials include soda-lime glass, silicate glass, metallic alloys, ionic melts, polymers, oxide glasses, glass-ceramics, etc. In some embodiments, the housing 600 houses an optical instrument and the window 615 is an optical window. In some embodiments, the window 615 is on the −Z side of the housing 600 and intersects the housing axis 630. The window 615 may be an aperture or other viewing structure. As shown, the housing may be substantially spherical and the window substantially planar. The housing 600 may be other shapes, as discussed above. Further, the window 615 may be different shapes. In some embodiments, the window 615 is planar as depicted in FIG. 2, but it may also be partially planar, rounded, concave, convex, spherical, elliptical, etc. or any combinations thereof.

[0054] In some embodiments, the device 500 is coupled to the housing 600. A side view of the device 500 is shown in FIG. 2 coupled to the housing 600. However, portions of the device 500 that would obscure the +Y side of housing 600 in the view as shown have been removed for clarity. The device 500 may be rigidly attached to the housing 600 with screws, rivets, bolts, adhesive, fasteners, etc. As is discussed in further detail herein, for example with respect to FIGS. 8A-8D, the device 500 may attach to an adapter 545 at an interface 800 with the housing 600. In some embodiments, the device 500 may attach to both the housing 600 and the adapter 545 at the interface 800 to the housing. Many configurations and assemblies of the device 500 with the housing 600, although not explicitly addressed herein, are within the scope of the present disclosure.

[0055] In some embodiments, the device 500 has a bottom surface 520, a top surface 510, and an outer perimeter 515. The bottom surface 520 may face the +Z side of the device 500. The top surface 510 may face the −Z side. The outer perimeter 515 may couple the bottom surface 520 to the top surface 510. The outer perimeter 515 may further be that portion of the device 500 that is farthest from the housing axis 630 when installed on the housing 600.

[0056] In some embodiments, the device 500 contains an upstream portion 550 and a downstream portion 555. The upstream portion 550 and/or the downstream portion 555 may contain the top surface 510, the bottom surface 520, and/or the outer perimeter 515. The upstream portion 550 and the downstream portion 555 may refer to portions or cross-sections of the device 500 that are aligned with or intersect the X axis. However, the portions 550, 555 may also refer to other portions or cross-sections of the device 500.

[0057] As shown, the device 500 may be curved. In some embodiments, the device 500 has curvature such that the top surface 510 and bottom surface 520 are totally or partially curved toward the housing 600, which may be in the +Z direction. In some embodiments, the upstream portion 550 and/or the downstream portion 555 contain a curvature. In some embodiments, the upstream portion 550 and the downstream portion 555 contain similar curvatures. In some embodiments, the upstream portion 550 and the downstream portion 555 contain different curvatures. In some embodiments, parts or portions of the upstream portion 550 and/or the downstream portion 555 are curved while other parts or portions are not curved. It is understood that discussion of any curvature of the upstream (+X) portion 550 and/or the down-

stream (−X) portion **555** may similarly apply to other portions of the device **500**. For example, although FIG. **1** depicts only +X and −X portions of the device **500**, other portions, such as +Y and −Y portions or portions between the +/−X and +/−Y portions, of device **500** may have similar features. Therefore, any features and/or capabilities as discussed with respect to one portion of the device **500** may apply, mutatis mutandis, to other portions of the device **500**, even if not explicitly indicated.

[0058] FIG. **2** further depicts a freestream flow field **700**. The direction of the flow of the flow field **700** is in the −X direction, as indicated by the arrows on the ends of the flow lines. The freestream flow field **700** may contain an upstream flow field **705** and a downstream flow field **710**, as shown. The upstream flow field **705** is that part of the freestream flow field **700** that is on the +X side of the subsystem **200** and flowing in the −X direction, i.e. flowing towards the subsystem **200**. The downstream flow field **710** is that part of the freestream flow field **700** on the −X side of the subsystem **200** and flowing in the −X direction, i.e. flowing away from the subsystem **200**. The upstream and downstream flow fields **705**, **710** may or may not contact the housing **600** or device **500**. In some embodiments, portions of the upstream flow field **705** contact portions of the housing **600** and/or device **500**. Therefore, in some embodiments, the fluid flow in the upstream flow field **705** contacts the upstream portions **550** of the device **500**, and the fluid flow contacting the downstream portions **555** of the device **500** leaves the device **500** and enters the downstream flow field **710**. It is further understood, therefore, that the location of the upstream portions **550** and/or downstream portions **555** may change if the direction of the freestream flow field **700** changes. For instance, the freestream flow field **700** may travel in the +X direction, such that the upstream portions **550** are on the −X side of the device **500** and the downstream portions **555** are on the +X side.

[0059] As shown in FIG. **2**, an upstream portion **550** of the device **500** extends into the upstream flow field **705** of the freestream flow field **700**. In some embodiments, the device **500** is configured to split the upstream flow field **705** into a first flow domain **715** and a second flow domain **720**. The respective domains **715**, **720** are indicated in FIG. **2** by respective hatching patterns.

[0060] In some embodiments, the extent of the first and second flow domains **715**, **720** may be designated by a flow domain boundary **717**. As depicted, the flow on the +Z side of the boundary **717** may be the second flow domain **720** and the flow on the −Z side of the boundary **717** may be the first flow domain **715**. The two domains **715**, **720** may or may not mix along that portion of the boundary **717** to the +X side of the device **500**. In some embodiments, the boundary **717** may have a thickness, such that a region of mixing defines the thickness. Therefore, the boundary need not be a line. It may be a band or other such region with a thickness. In some embodiments, the freestream flow field **700** is laminar and the two domains **715**, **720** do not mix along that portion of the boundary **717** to the +X side of the device **500**.

[0061] As depicted, the boundary **717** contacts the device **500** at the outer perimeter **515**. In some embodiments, the boundary **717** may contact the device **500** in other locations, such as the top surface **510**, the bottom surface **520**, and/or other locations. For instance, if the device **500** is rotated about the Y axis **310**, the boundary **717** may contact the device on the top surface **510** or bottom surface **520**, depending on the direction of rotation relative to the direction of the freestream flow field **700**. Further, the scope or locations of the two domains **715**, **720** may be larger than is indicated in FIG. **2**. For instance, the second flow domain **720** may extend farther in the +Z and −X directions, while the first flow domain **715** may extend farther in the −Z and −X directions. For clarity, only portions of the two domains **715**, **720** are shown.

[0062] As depicted, the second flow domain **720** contacts the upstream portion **550** of the device **500**. The second flow domain **720** may contact the upstream portion **550** at the outer perimeter **515**. In some embodiments, the second flow domain **720** continues along and over the +Z side of the outer perimeter **515** and then along and over the bottom surface **520**. As is discussed in further detail herein, for example with respect to FIG. **5**, the second flow domain **720** may be attached, separated, or a combination of the two along or over the outer perimeter **515** and/or the bottom surface **515**. The second flow domain **720** on or over the outer perimeter **515** and the bottom surface **520** may thus be laminar, turbulent, etc. or combinations thereof.

[0063] In some embodiments, the second flow domain **720** also contacts the housing **600**. As shown, the second flow domain **720** contacts the moveable housing structure **605**. The second flow domain **720** may also contact the static housing structure **610** and/or any other parts of the housing **600**, as well as the vehicle **400** (not shown). Further, the second flow domain **720** may flow around any of these parts. For example, the second flow domain **720** may also flow around the +Y and −Y sides of the housing **600**. In some embodiments, the second flow domain **720** may also flow along the downstream portion **555** of the device **500** and contact the bottom surface **520** and/or the outer perimeter **515**. The second flow domain **720** may then leave the device **500** and enter the downstream flow field **710**, which is in the −X direction relative to the device as shown.

[0064] As depicted, in some embodiments the first flow domain **715** may contact the upstream portion **550** of the device **500**. The first flow domain **715** may initially contact the upstream portion **550** at the outer perimeter **515** or the top surface **510**. In some embodiments, the first flow domain **715** continues along the −Z side of the outer perimeter **515** and then along the top surface **510**. The first flow domain **715** may then continue along the window **615** that is between the upstream portion **550** and the downstream portion **555** of the device **500**. The first flow domain **715** may then continue to the downstream portion **555** of the device **500**. At the downstream portion **555**, the first flow domain **715** may flow along the top surface **510** and/or the outer perimeter **515**. Further, the first flow domain **715** may flow on, over and/or around the device **500** and/or the housing **600**. For example, the first flow domain **715** may flow on, over and/or around the +Y and −Y sides of the device **500** along the outer perimeter **515** and/or the top surface **510**. In some embodiments, the first flow domain **715** may be attached, separated, or a combination of the two along the outer perimeter **515**, the top surface **510** and/or the window **615**. The first flow domain **715** on or over the −Z side of the outer perimeter **515**, the top surface **510**, and/or the window **615** may thus be laminar, turbulent, etc. or combinations thereof. Further, as is discussed in further detail herein, for example with respect to FIG. **5**, a region or regions of aero-optical flow may be present in the first flow domain **715** in any location or locations along the device **500** and window **615**, including but not limited to the upstream portion **550** and/or downstream portion **555** of the device **500** and/or the window **615**. The first and second flow domains **715**, **720**

may mix in the downstream flow field **710** to the −X side of the downstream portion **555** of the device **500**.

[0065] In some embodiments, the subsystem **200** may include the device **500** as integral with the housing **600**. In some embodiments, the subsystem **200** may include the housing **600** and the device **500** that is integral with the housing. In some embodiments, the device **500** that is integral with the housing **600** protrudes from the housing **600** in the form of a lip, flange, rim, flare or structure with a shape and/or geometry that resembles the device **500** as described herein. The device **500** may be integral with the moveable housing structure **605**, the window **615**, and/or any other parts or components of the subsystem **200**. In some embodiments, the integral device **500**, such as in the form of a lip, is configured to split the freestream flow field **700** into the first flow field **715** above the lip and window **615** and a second flow field **720** under the lip and around the housing **600**. In some embodiments, the first flow field **715** comprises an aero-optical flow region that extends at least partially over the top surface **510** of the lip and continues at least partially over the window **615**. In some embodiments, the aero-optical flow region is maintained within a range of angular orientations of the axis **630** relative to the freestream flow, as is discussed in further detail herein, for example with respect to FIG. **6**.

[0066] FIGS. **3**A and **3**B depict bottom views of different embodiments of the device **500** with the window **615** as viewed from the direction indicated in FIG. **2**. For clarity, other structures of the housing **600** are not shown in FIGS. **3**A and **3**B. As shown in both FIGS. **3**A and **3**B, the device **500** is configured around the window **615**. The window **615** may have an outer perimeter **617**. As shown, the outer perimeter **617** may be flat on two sides and rounded on two sides. Other shapes and configurations of the outer perimeter **617** are possible. In some embodiments, the outer perimeter **617** is completely rounded, circular, elliptical, etc. or it may be a polygonal shape with multiple sides such as a square, or combinations thereof.

[0067] The device **500** may further have an inner perimeter **505**. In some embodiments, the inner perimeter **505** may complement the outer perimeter **617** of the window **615**. For example, the window **615** as shown has an outer perimeter with two flat sides and two rounded sides, and the inner perimeter **505** of the device **500** likewise has two each of complementary flat sides and rounded sides that complement the respective sides of the window **615**. Therefore, in some embodiments, the contours of the various sides of the inner perimeter **505** match, copy, correspond, pair with, align, imitate, replicate, emulate, mimic or otherwise complement the outer perimeter **617** of the window **615**. Further, while the inner perimeter **505** is shown complementing the window outer perimeter **617**, the inner perimeter **505** may instead or in addition complement other features of the housing **600**. In some embodiments, the inner perimeter **505** may complement an object such as a seal or adapter between the device **500** and the housing **600**, as is discussed in further detail herein, for example with respect to FIGS. **4**, **8**B and **8**C.

[0068] The device **500** may further be arcuate, as shown in FIGS. **3**A and **3**B. In some embodiments, the top surface **510** and/or outer perimeter **515** are arcuate. For example, the top surface **510** and outer perimeter **515** may be swept around and thereby form an arc or arcs around the window **615** and/or other features of the housing **600**. The arc may be any number of arcuate shapes including an arc or arch, and it or they may be curved, circular, semicircular, elliptical, may be combinations thereof, may have smooth and/or sharp transitions between various different arcuate sections, etc. In some embodiments, the bottom surface **520** may also be arcuate. In some embodiments, the bottom surface **520** is similarly arcuate as the top surface **510** and/or outer perimeter **515**. The various arcuate features may thus be similarly or differently arcuate for a given angular location or circular coordinate of the device **500**.

[0069] As shown, the top surface **510** and outer perimeter **515** may be arcuate around a portion of the window **615**. As shown, the device **500** sweeps out an arc for an angular amount indicated by an angle of sweep **540**. In some embodiments, the angle **540** is less than three hundred and sixty degrees, for example three hundred degrees. The angle **540** may be other amounts as well, including ninety degrees, one hundred and eighty degrees, two hundred and seventy degrees, etc. In FIG. **3**B, the device completely surrounds the window **615** such that the angle **540** is three hundred and sixty degrees.

[0070] For devices sweeping out angles **540** that are less than three hundred and sixty degrees, the device **500** may have one or more end surfaces **560**. The end surfaces **560** as shown in FIG. **3**A are on either end of the arcuate arc swept out by the device **500**. The end surface **560** may be any number of shapes at various orientations. In some embodiments, the end surface **560** has a smooth trailing edge. In some embodiments, the end surface **560** has an abrupt blunt end. In some embodiments, the end surface **560** is tapered. In some embodiments, the device **500** has end surfaces **560** that are symmetric about a plane (such as the X-Z plane as oriented in FIG. **2**). In some embodiments, the device **500** has end surfaces **560** that are asymmetric,

[0071] In some embodiments, the device **500** may be positioned in different orientations with respect to the direction of the freestream flow field **700**. The free stream flow field **700** may thus approach the device **500** from different directions. As shown in FIGS. **3**A and **3**B, the device **500** may be rotated or otherwise moved such that the freestream flow field **700** approaches the device in the direction indicated by arrow **701**, by arrow **702**, or by arrow **703**. The freestream flow field **700** may further approach the device **500** from other directions and/or any directions therebetween, including directions opposite of those indicated by arrows **701**-**703**. Further, the freestream flow field **700** may likewise approach the device **500** in different planes, for instance if the device rotates about the Y axis **310**, as is discussed in further detail herein for example with respect to FIG. **6**.

[0072] FIG. **4**A depicts a section view of an embodiment of the upstream portion **550** of the device **500** and housing **600** with window **615**. In some embodiments, the inner perimeter **505** is coupled to the top surface **510**, which is coupled to the outer perimeter **515**, which is coupled to the bottom surface **520**. In some embodiments, the device **500** is an integral, single, or otherwise monolithic piece such that the inner perimeter **505**, the arcuate top surface **510**, the outer perimeter **515** and the bottom surface **520** refer to various locations of the same piece. In some embodiments, the inner perimeter **505**, the top surface **510**, the outer perimeter **515**, the bottom surface **520**, and parts or combinations thereof are separate parts that are combined to form the device **500**. For instance, each may be a separate part such that the device **500** constitutes four surfaces that may be joined to form the complete device **500**. Or, for example, the top surface **510** and outer perimeter **515** may be a first integral part and the bottom

surface **520** and inner perimeter **505** may be a second integral part. The first and second integral parts may then be joined to form the complete device **500**. It is thus understood that any and all of these or other configurations known to the art may constitute a "coupling" of the inner perimeter **505**, the top surface **510**, the outer perimeter **515** and the bottom surface **520**. The description of one such configuration is not meant to limit the scope of the present disclosure.

[0073] The device **500** may be made from any number of suitable materials. In some embodiments, the device **500** is metallic. The device **500** may instead or in addition be plastic, polymeric, ceramic, composite, fiber, or any combinations thereof. Further, the device **500** may be solid, hollow, or any combinations thereof, such as semi-porous and/or having a non-uniformly distributed material density. In some embodiments, the device **500** includes the same material as the housing **600**. For instance the device **500** may be integral with the housing **600** and thus constitute similar materials and/or material properties as the housing **600**. In some embodiments, the device **500** is completely impermeable to fluid flow. For example, the device **500** may be sealed so that the flow of fluid such as air or water may not be able to penetrate, permeate, enter, pass through, seep into, or otherwise get into or through the device **500**.

[0074] In some embodiments, the inner perimeter **505**, the top surface **510**, the outer perimeter **515** and the bottom surface **520** together form a closed contour that defines an outer boundary or edge of a cross section of the device **500**. In some embodiments, the device **500** includes a plurality of such cross sections. In some embodiments, at least one of the cross sections is arcuately swept or otherwise extended or extruded at least partially around the outer perimeter **617** of the window **615**. In some embodiments, at least one of the cross sections is swept at least 180 degrees around the outer perimeter **617** of the window **615**. In some embodiments, at least one of the cross sections is swept at least partially into the upstream flow field **705**. In some embodiments, at least one of the cross sections is in a plane such that at least part of the upstream flow field **705** in the plane is perpendicular to a line that is tangent to a point on an edge of the cross section. Although FIG. **4**A depicts a cross section of the device **500** that is located on the upstream portion **550** of the device **500**, this cross section could be located at any angular position along the arcuate device **500**, including the downstream portion **555**.

[0075] In some embodiments, the outer perimeter **515** is the farthest feature of the device **500** from the housing axis **630**. In some embodiments, the outer perimeter **515** is a leading edge and faces the upstream flow field **705**. In some embodiments, a segment of the contour of the cross section of the outer perimeter **515** is rounded. The outer perimeter **515** may also comprise one or more radial, elliptical, and/or straight segments, or any combinations thereof. For instance, the outer perimeter **515** may have various segments each with varying radii of curvature. It may further follow a contour defined by an equation or function describing a rounded surface configured for inducing aero-optical flow.

[0076] In some embodiments, the outer perimeter **515** is coupled to the bottom surface **520**. The transition from the outer perimeter **515** to the bottom surface **520** may be smooth. Further, the outer perimeter **515** may transition to the bottom surface **520** on the +X side of the device **500** or on the +Z side of the device **500**. In some embodiments, the bottom surface **520** faces the second flow domain **720**. As shown, this may be on the +Z side of the device **500** which also may partially face the housing **600**.

[0077] In some embodiments, the outer perimeter **515** is coupled to the top surface **510**. The transition from the outer perimeter **515** to the top surface **510** may be smooth. Further, the outer perimeter **515** may transition to the top surface **510** on the +X side of the device **500** or on the −Z side of the device **500**. In some embodiments, the top surface **510** faces the first flow domain **715**. As shown, this may be on the −Z side of the device **500** which may also face away from the housing **600**. In some embodiments, the top surface **510** and the outer perimeter **515** form a substantially smooth surface.

[0078] In some embodiments, the top surface **510** has an inner portion **525**. The inner portion **525** is the area or region of the top surface **510** that is nearest or adjacent to the housing **600**. In some embodiments, it is the last portion of the top surface **510** over which fluid in the first flow domain **715** flows before it reaches the housing **600**, which may be the moveable housing structure **605** such as a wall or edge of a wall of the structure **605**.

[0079] In some embodiments, the inner portion **525** of the top surface **510** is coupled to the bottom surface **520** via the inner perimeter **505**. Thus the bottom surface **520**, the outer perimeter **515**, the top surface **510** and the inner perimeter **505** may form a continuous surface of device **500**. The transition **507** from the inner portion **525** of the top surface **510** to the inner perimeter **505** may be sharp, as shown. The transition **507** may also be smooth, stepped, or any combinations thereof. The transition **517** from the bottom surface **520** to the inner perimeter **505** may likewise be sharp, as shown, or it may be smooth, stepped, or any combinations thereof.

[0080] In some embodiments, the top surface **510** and the bottom surface **520** define a thickness **530**. In FIG. **4**A, the thickness **530** is indicated at two different sections of the device **500** by the dashed, double arrowed lines. These are merely illustrative locations of the thickness, and it is understood that the thickness **530** may be located anywhere between the top surface **510** and the bottom surface **520**. In some embodiments, the thicknesses **530** shown in FIG. **4**A are different lengths, such that the thickness **530** of the device **500** is not uniform. In some embodiments, the thickness is uniform, substantially uniform, substantially nonuniform, or any combinations thereof. For example, the thickness **530** may be uniform for most of the device **500** with a minority portion near the outer perimeter **515** tapering into a smaller thickness **530**. Thus, in some embodiments, the thickness **530** may also be between various parts of the segment defining the outer perimeter **515**. By "uniform" it is understood that this refers to a thickness that is the same over an indicated portion. By "nonuniform" it is understood that this refers to a thickness that changes, in any manner, at any two sections of the device from the outer perimeter **515** of the device to the inner perimeter **505**. For example, nonuniform includes a thickness **530** that tapers smoothly or that changes abruptly. Further, the device **500** may have a uniform thickness **530** in one cross section of the device **500** but have a nonuniform thickness in **530** another cross section of the device **500**. Therefore, the thickness **530** may change along the arcuate sweep of the device **500**. In some embodiments, the thickness **530** at or near the inner perimeter **505** is about three quarters of an inch (0.75").

[0081] As further shown in FIG. **4**A, the device **500** has a curvature. In some embodiments, the curvature of the device

500 curves toward the second flow domain 720 and/or toward the housing 600. In some embodiments, the top surface 510 has a curvature. In some embodiments, the bottom surface 520 has a curvature. The curvature of the top surface 510 may be radial, elliptical, convex, bulging, arched, protuberant, raised, may be defined by an equation, or any combinations thereof. The curvature of the bottom surface 520 may be radial, elliptical, concave, cupped, sunken, arched, may be defined by an equation, or any combinations thereof. The curvature of the surfaces 510, 520 may further include straight sections. For example, the top surface 510 may comprise a first curvature, then a straight section, and then a second curvature. Other configurations and variations of the curvature of the device 500, although not explicitly addressed herein, are within the scope of the present disclosure.

[0082] Further, the bottom surface 520 may have a variety of different curvatures. In some embodiments, the bottom surface 520 may have none or very little curvature. For example, the bottom surface 520 may be substantially straight. In some embodiments, the bottom surface 520 may have a curvature that is symmetric with the top surface 510. In some embodiments, portions of the bottom surface 520 near the housing 600 may curve farther in the +Z direction, as oriented in FIG. 4A, such that the bottom surface 520 eventually gradually matches the slope of a part of the housing 600, such as the moveable structure 605.

[0083] In some embodiments, the device 500 has a camber defined by a camber line 522. The camber line 522 may be a line halfway between the upper surface 510 and lower surface 520. Thus, the contour of the camber line 522 may be indicative of the curvature of the device 500. For example, as shown in FIG. 4A, the camber line 522 curves toward the +Z direction, as does the curvature. In some embodiments, the top surface 510 may be symmetric with the bottom surface 520 such that the top and bottom surfaces 510, 520 may be equidistant from the camber line 522 at a given section. This may be seen along the thicknesses 530 indicated in FIG. 4A, where the top surface 510 may be the same distance as the bottom surface 520 from the camber line 522 at these thicknesses 530. In some embodiments, the camber line 522 is curved with any number of extrema and inflection points. In some embodiments, therefore, the camber line 522 may be reflexed such that the camber line 522 curves back up near the housing 600 toward the inner portion 525. In some embodiments, the camber line 522 is straight.

[0084] As further depicted in FIG. 4A, the device 500 and the housing 600 form an interface 800. The interface 800 between the device 500 and housing 600 may be in a number of configurations. As shown, in some embodiments the device 500 complements a seal 535 that is between the device 500 and the housing 600. In some embodiments, the inner perimeter 505 of the device 500 complements the seal 535. In some embodiments, the inner perimeter 505 adheres to, is fastened to, attaches to, or otherwise mechanically couples with the seal 535. In some embodiments the seal 535 is a separate part from the device 500 and the housing 600. For instance, the seal 535 may couple with the inner perimeter 505 and the housing 600, such as the moveable housing structure 605. In some embodiments, the seal 535 is integral with the device 500. In some embodiments, the seal 535 is integral with the housing 600.

[0085] In some embodiments, the seal 535 may have an elongated cross section such that it completely separates the device 500 from the housing 600. In some embodiments, the seal 535 is as wide as it is thick, or wider. In some embodiments, the seal 535 may have a round cross section. In some embodiments, the seal 535 may have a larger cross sectional area as compared to after it is coupled in the interface 800 between the device 500 and the housing 600. In some embodiments, the seal 535 may not entirely separate the device 500 from the housing 600. For instance, the seal 535 may only separate a portion of the inner perimeter 505 from the housing 600, while another portion of the inner perimeter 505 butts directly against or is otherwise mechanically coupled directly with the housing 600. In some embodiments, the inner perimeter 505 may have a stepped contour where the seal 535 has a complementary stepped contour. In some embodiments, the seal 535 may be between the bottom surface 520 and/or top surface 510 of the device 500 and the housing 600. For instance, the seal 535 may have a U-shaped cross section that surrounds the inner perimeter 505, the inner portion 525 or more of the top surface 510 and/or an inner portion or more of the bottom surface 520.

[0086] In some embodiments, the seal 535 has an arcuate shape such that a cross section of the seal 535 is swept, extended, or otherwise extruded around the housing 600 for an angular amount defining a swept contour. In some embodiments, the angular amount is equal or similar to the angle of sweep 540, which corresponds to the angle of sweep 540 of the device 500 (see FIG. 3A). In some embodiments, the angular amount of sweep of the seal 535 is less or more than the angle 540. In some embodiments, the seal 535 is continuous along the entire angular amount of sweep. In some embodiments the seal 535 is discontinuous, such that in some locations along the sweep it has different cross sections. In some embodiments, the seal 535 is comprised of multiple subparts located at various angular locations along the swept angular contour. Further configurations and details of the interface 800 between the device 500 and the housing 600 are discussed herein, for example with respect to FIGS. 8A-8D.

[0087] In some embodiments, the seal 535 may prevent, mitigate, or otherwise restrict the passage of fluid from the second flow domain 720 to the first flow domain 715, and vice versa, at the interface 800. In some embodiments, the seal 535 creates an interface 800 that is entirely impermeable to the freestream flow field 700, the first flow field 715 and the second flow field 720, where absolutely no fluid flow is allowed to pass between the device 500 and the housing 600 at the interface 800. The seal 535 may therefore prevent fluid communication between the first and second flow fields 715, 720 at the interface 800. In some embodiments, the seal 535 creates an interface 800 that is substantially impermeable to the freestream flow field 700, the first flow field 715 and the second flow field 720, where there is negligible passage of fluid from the second flow domain 720 to the first flow domain 715, or vice versa, via the interface 800 between the device 500 and the housing 600. The standard for "negligible" as used here is the creation of a region of aero-optical flow in the first flow domain 715. If the passage of fluid through the interface 800 is such that is does not allow for the creation of a region of aero-optical flow, then the passage is more than negligible. "Substantially impermeable" therefore also captures configurations where some flow is allowed to pass between the device 500 and housing 600 but which does not disrupt the flow in the manner described. It is understood that other configurations of the interface 800 between the device 500 and the housing 600, either with or without the seal 535, may provide the same functionality as described above. For

instance, the device **500** itself may provide a sealing function such as with the inner perimeter **505** butted against or otherwise mechanically coupled to the housing **600**, as is shown and discussed in further detail herein, for example with respect to FIGS. **5** and **8**A-**8**D.

[0088] In some embodiments, the device **500** may be flush with the housing **600**. In some embodiments, portions or parts of the device **500** are flush with portions or parts of the housing **600**. For instance, the inner portion **525** may be level with an edge of the moveable housing structure **605**. In some embodiments, the inner portion **525** of the top surface **510** is configured to be substantially flush with an outer portion **620** of the window when the device **500** is coupled with the housing **600**. In some embodiments, the inner portion **525** is flush or substantially flush with an edge of the seal **535**, which is flush or substantially flush with an edge of the housing structure **605**. In some embodiments, the inner portion **525** extends in a parallel manner from the housing structure **605** and/or the window **615**. For instance, the window **615** may be flat and the inner portion **525** may likewise be flat and extend away from the window for a given length, such that the inner portion **525** continues the surface of the window **615** for that length.

[0089] In some embodiments, the device **500** may be contiguous with the housing **600**. In some embodiments, an inner portion **525** of the top surface **510** is substantially contiguous with the outer portion **620** of the window **615** when the device **500** is coupled with the housing **600**. In some embodiments, an inner portion **525** of the top surface **510** is substantially contiguous with an edge of the seal **535**, which is substantially contiguous with the outer portion **620** of the window **615**, such that a substantially contiguous surface is formed by the inner device portion **525**, the edge of the seal **535**, and the inner window portion **620**. In some embodiments, the inner device portion **525**, the inner window portion **620**, and/or an edge of the seal **535** are coplanar. In some embodiments, the inner device portion **525**, the inner window portion **620**, and/or an edge of the seal **535** are not coplanar. In some embodiments, the slope of the inner device portion **525** substantially matches the slope of the outer window portion **620**. In some embodiments, the slope of the inner device portion **525** substantially matches the slope of an edge of the seal **535**, which substantially matches the slope of the outer window portion **620**. Other configurations at the interface **800** are discussed further herein, for example with respect to FIGS. **8**A-**8**D.

[0090] FIG. **4**B depicts geometric features of a section view of an embodiment of an upstream portion of the device **500**. As shown, the geometry of the device **500** may be described in part by an inner portion length **526**, a top surface length **511**, and a top surface height **512**. The inner portion length **526** refers to the horizontal distance from one end of the inner portion **525** to the opposite end in a direction that is perpendicular to the housing axis **630**. In some embodiments, the inner portion **525** is flat and perpendicular to the housing axis **630**, as shown. Thus, the inner portion length **526** may be the same as the length of the inner portion **525**. In some embodiments, the inner portion **525** is rounded, partially rounded, partially flat, flat but at an angle to the axis **630**, or combinations thereof. Thus the inner portion length **526** may be different from the length of the inner portion **525**. In some embodiments, the inner portion **525** is flat and perpendicular to the axis **630**, and the inner portion length **526** is about half an inch (0.5").

[0091] The top surface length **511** refers to a horizontal distance of the top surface **510** beyond the inner portion **525** in a direction that is perpendicular to the housing axis **630**. As shown, the top surface length **511** extends from an end of the inner portion **525** that is farthest from the axis **630** and continues perpendicularly outward away from the axis **630** until it is coextensive with the outer-most edge of the device **500**. This outer-most edge may be the outer perimeter **515**, the top surface **510**, or a transition point **514** between the two. In some embodiments, the top surface length **511** is within the range of one and one half inches (1.5") to two and one quarter inches (2.25"), inclusive. In some embodiments, the top surface length **511** is about two and one quarter inches (2.25").

[0092] The top surface height **512**, as shown, refers to a vertical distance from one end of the inner portion **525** of the top surface **510** to a transition point **516** between the top surface **510** and the outer perimeter **515**. In some embodiments, the top surface height **512** is within a range from eighty-five hundredths of an inch (0.85") to one and one half inches (1.5"), inclusive.

[0093] The geometry of the device **500** may further be defined by an aspect ratio. The aspect ratio is the ratio of the top surface length **511** to the top surface height **512**. In some embodiments, the aspect ratio is within the range of one and one half (1.5) to one and three quarters (1.75), inclusive. In some embodiments, the window **615** is twelve and eight-tenths inches (12.8") across, the inner portion length **526** is one half inch (0.5"), the top surface length **511** is two and one quarter inches (2.25"), the top surface height **512** is one and one half inches (1.5"), and thus the aspect ratio is one and one half (1.5).

[0094] Further shown in FIG. **4**B is the outer perimeter **515** having a radius. In some embodiments, the outer perimeter **515** transitions to the top surface **510**, and vice versa, at transition point **514**. In some embodiments, the outer perimeter **515** transitions to the bottom surface **520**, and vice versa, at transition point **516**. The transition points **514**, **516** may be locations on the edge of the device **500** where the respective surfaces share a tangency. For instance, at transition point **514**, both top surface **510** and outer perimeter **515** may have similar slopes. Thus a line tangent to the top surface **510** at transition point **514** has the same slope as a line tangent to the outer perimeter **515** at transition point **514**. This may also apply to transition point **516**. As shown, the outer perimeter **515** is a radius that is tangent to the top surface **510** at transition point **514** and to the bottom surface **520** at transition point **516**. In some embodiments, the outer perimeter **515** has a radius within the range of one quarter inch (0.25") to one sixteenth of an inch (0.0625"), inclusive. In some embodiments, the radius of the outer perimeter **515** is one sixteenth of an inch (0.0625").

[0095] The device **500** may also have the thickness **530** as shown where the device **500** interfaces with the housing **600**. In some embodiments, the thickness is about three-quarters of an inch (0.75"). Therefore, in some embodiments of device **500**, the inner portion **525** near the housing **600** is three-quarters of an inch (0.75") thick, the inner portion length **526** is one half of an inch (0.5"), the top surface length **511** is two and one quarter inches (2.25"), the top surface height **512** is one and one half inches (1.5"), the aspect ratio is one and one half (1.5), and the outer perimeter **515** is rounded with a radius of one sixteenth of an inch (0.0625").

[0096] The various configurations for the interface **800** between the device **500** and the housing **600** allow for smooth

and substantially uninterrupted flow of fluid from at least the inner portion **525** of device **500** to the outer portion **620** of the window **615**, such that the flow is more conducive for successful operation of an optical instrument in the housing **600**. The flow of fluid at and around the interface **800** will now be discussed with respect to FIG. **5**.

[0097] FIG. **5** depicts embodiments of the first and second flow domains **715**, **720** at and around the interface **800** of the device **500** and housing **600**. As shown, the first flow domain **715** contains a region **733** with aero-optical flow, as indicated by the cross-hatched area. As noted elsewhere herein, aero-optical flow as used herein refers to flow with reduced density gradients as compared to flow over the housing **600** without the device **500**. The reduced gradients in the region **733** may be in planes perpendicular to the housing axis **630**, which may or may not be aligned with the Z axis **315**.

[0098] In some embodiments, the region **733** may extend from the upstream portion **550** of the outer perimeter **515** across the entire window **615** and to the outer perimeter **515** at the downstream portion **555** (shown in FIG. **2**) of the device **500**, or any portion or portions thereof. In some embodiments, the region **733** may extend at least partially over the top surface **510** and continue at least partially over the window **600**. As shown, in some embodiments the region **733** may extend from the inner device portion **525** to the outer window portion **620**. The region **733** may contact those parts over which it is present. For example, the region **733** in FIG. **5** may contact the inner device portion **525**, the housing structure **605**, and the outer window portion **615**. The region may extend away from the device **500** and housing **600** in the −Z direction, as oriented in FIG. **5**. In some embodiments, the extent of the region **733** in the −Z direction, as oriented, is similar to a diameter or width of the window **615**.

[0099] FIG. **5** further depicts an optical instrument field of view (FOV) **625**. The FOV **625** is the area through which the electromagnetic energy is transmitted and/or received by an instrument inside the housing **600**. As depicted, the FOV **625** is abbreviated or shortened. FIG. **5** only shows that portion of the FOV **625** that intersects with the portion of the region **733** that is depicted. In some embodiments, the FOV **625** may extend further in the +Z and/or −Z directions, as well as further in the +X and/or −X directions.

[0100] By inducing reduced density gradients in the region **733**, the device **500** improves the flow near the housing **600** and window **615**. This improved near-field flow prevents, reduces and/or mitigates aberrations in the wavefront of electromagnetic energy being transmitted and/or received by an optical instrument through the housing window **630**.

[0101] The optical instrument may operate in the optical or visual band of the electromagnetic spectrum. For an instrument operating in this band, the quality of the medium through which it travels may be characterized by a Strehl ratio. The Strehl ratio is a measure of the quality of optical image formation or of optical resolution in the medium, such as an atmosphere. In some embodiments, the device **500** controls the fluid flow in the instrument's FOV **625** such that it improves the Strehl ratio. In some embodiments, the Strehl ratio in the region **733** is at least 0.7 for electromagnetic radiation at a wavelength of about 1 micrometer.

[0102] As mentioned, the first flow domain **715** may be separated from the second flow domain **720** by the boundary **717**. The scope or extent of the two domains **715**, **720** as shown in FIG. **5** is for illustration only. The domains **715**, **720** may continue farther in the +/−X, Y, and/or Z directions. FIG. **5** (and FIG. **2**) illustrates that some flow lines from the freestream flow field **700** end up in the first flow domain **705** and others end up in the second flow domain **720**. In between, the boundary **717** may contact the device **500** at a point **718**. In some embodiments, the point **718** may be a stagnation point. Stagnation points exist at the surface of objects in a flow field where the fluid is brought to rest by the object. Thus, the point **718** may be a point where the local velocity of the fluid is zero. The areas of flow along the device **500** that are downstream of and on either side (+/−Z as oriented) of the point **718** are thus the two flow domains **715**, **720**.

[0103] As shown, in some embodiments the point **718** may be on the outer perimeter **515**. In some embodiments, the point **718** may be in other locations on the outer perimeter **515**, on the top surface **510**, or on the bottom surface **520**. The location of the point **718** will depend in part on the orientation of the device **500** relative to the freestream flow field **700**.

[0104] Further, the second flow domain **720** may include the flow along the bottom device surface **520** and/or along the housing **600**. In some embodiments, the second flow domain **720** flows along the moveable housing structure **605** and/or along the static housing structure **610** (not shown in FIG. **5**). Further, the second flow domain **720** may have a region or regions of aero-optical flow or any other flow, including turbulent, separated, flow with vortices, etc.

[0105] FIG. **6** depicts a side view of the device **500** rotated relative to the freestream flow field **700**. As shown, the device **500** is rotated about the Y axis **310** by an elevation angle **311**. In some embodiments, the rotation of the device is about the X, Y and/or Z axes. In some embodiments, the rotation is about a roll angle **306**, the elevation angle **311**, and/or an azimuth angle **316**, respectively. In some embodiments, the rotation about any of the axes can sweep out a total angle of plus or minus one hundred and thirty five degrees. In some embodiments, the total swept out angles are one hundred and eighty degrees, or more.

[0106] As shown, the moveable structure **605** of housing **600** is rotated about the Y axis **310** over the elevation angle **311**. In some embodiments, the device **500** is rigidly coupled to the housing **600** such that the device **500** rotates a similar amount as the housing **600**. In some embodiments, the optical instrument housing **600** has two or more degrees of freedom such that it can move in at least two dimensions. In some embodiments, the optical instrument housing **600** is rotatable about the Y axis and the Z axis.

[0107] As shown, the second flow domain **720** extends from the +Z side of point **718**, over the outer perimeter **515**, and over the bottom surface **520**. For clarity, the flow of the second flow domain **720** over the housing **600** is not shown. The first flow domain **715** extends from the −Z side of point **718** on the upstream portion **550** of the top surface **510**, over the window **615**, and over the downstream portion **555** of the top surface **510**. The first domain **715** further has an aero-optical flow region **733** over the window **615** and over portions of the device **500**. In some embodiments, the region **733** is maintained over a range of angular orientations of the device **500** relative to the direction of the freestream flow field **700**. In some embodiments, the region **733** is maintained for angular orientations of the device **500** about any of the axes of plus or minus one hundred and thirty five degrees. In some embodiments, the region **733** is maintained over angular orientations of the device **500** about any of the axes of plus or minus one hundred and eighty degrees or more.

[0108] As shown in FIG. **7**, the device **500** may be coupled to a housing **600** and subject to a freestream flow field **700** with an aero-optical flow region **733**. In some embodiments, a boundary layer **745** may form. The boundary layer **745** may encompass the aero-optical flow region **733**, or the aero-optical flow region **733** may encompass the boundary layer **745**, or the aero-optical flow region **733** may be co-extensive with the boundary layer **745**. In some embodiments, the boundary layer **745** is entirely or substantially in the first flow domain **715**. The boundary layer **745** may extend from across the upstream portion **550** of the device **500**, over the window **615**, and over the downstream portion **555** of the device **500**. In some embodiments, the boundary layer **745** is continuous or substantially continuous from the upstream portion **550** of the device **500** to the downstream portion **555**. The boundary layer **745** may also be intermittent or continuous over any parts thereof. The boundary layer **745** may contact the various surfaces of the device **500** and housing **600** over which it is located. It may also extend away from the various surfaces, approximately in the −Z direction as oriented in FIG. **7**.

[0109] In some embodiments, the boundary layer **745** has upstream and downstream velocity profiles **760**, **765**. As shown, the upstream velocity profile **760** is upstream relative to the downstream velocity profile **765** which is further downstream. The velocity profiles **760**, **765** indicate the relative speed of the flow as indicated by the length of the arrows in the profiles **760**, **765**. For example, the arrows closer to the device **500** are shorter than the arrows farther from the device **500**, indicating that the speed of the flow increases with increasing distance from the device **500**. In some embodiments, the speed of the flow at the surface of the device **500** is zero. In some embodiments, the speed of the flow in the boundary layer **745** that is farthest from the device **500** is at least ninety-nine percent of the speed of the flow in the freestream flow field **700**. In some embodiments, the velocity profiles have thicknesses **770**, **775**. The thicknesses **770**, **775** may be defined by the distance necessary for the speed of the flow in the boundary layer **745** to be ninety-nine percent of the speed of the flow in the freestream flow field **700**.

[0110] As shown, the upstream velocity profile **760** is over the inner portion **525** of the device **500** and the downstream velocity profile **765** is over the window **615**. However, the upstream velocity profile **760** may be in any position upstream of downstream velocity profile **765**. In some embodiments, the upstream and downstream velocity profiles **760**, **765** are substantially similar. In some embodiments, the length of the velocity arrows, and hence the speed of the flow at a given distance from the respective surfaces, are approximately the same for the two velocity profiles **760**, **765**. In some embodiments, the thicknesses **770**, **775** are approximately the same length.

[0111] In some embodiments, the boundary layer **745** includes laminar boundary layer portions **750**, **755**. As shown, the boundary layer **745** may include a laminar boundary layer portion **750** over the inner portion **525** of the top surface **510** of the device **500**. The laminar portion **750** may instead or in addition be over any other part of the device **500**, including upstream and/or downstream portions **550**, **555** of the device **500**. Further, the boundary layer **745** may include a laminar boundary layer portion **755** over the window **615**. The laminar portion **755** may instead or in addition be over any other part of the window **615**, including the outer window portion **620**. Therefore, the laminar boundary layer portions **750**, **755** may or may not coincide with the indicated locations of the velocity profiles **760**, **765** in FIG. **7**.

[0112] FIGS. **8**A-**8**D depict various embodiments of the interface **800** between the device **500** and a perimeter associated with the housing **600**. By "perimeter," unless indicated otherwise, it is understood that this includes any perimeter which the device **500** may interface **800** with when installed or otherwise assembled with the housing **600** and any other parts at the interface **800**. The interface **800** may include the inner perimeter **505** of the device **500**, the moveable housing structure **605**, the outer perimeter **617** of the window **615**, the outer portion **620** of the window **615**, and/or other parts. In some embodiments, the inner perimeter **505** is configured to complement the moveable housing structure **605**, the outer perimeter **617** of the window **615**, the outer portion **620** of the window **615**, and/or other parts. In some embodiments, when the device **500** is coupled with the housing **600**, the inner portion **525** of the top surface **510** is configured to be substantially flush with the outer portion **620** of the window **615**, with other parts of the housing **600**, and/or with any other parts at the interface **800**. In some embodiments, when the device **500** is coupled with the housing **600**, the inner portion **525** of the top surface **510** is configured to be substantially contiguous with the outer portion **620** of the window **615**, with other parts of the housing **600**, and/or with any other parts at the interface **800**. In some embodiments, when the device **500** is coupled with the housing **600**, the slope or slopes of the inner portion **525** of the top surface **510** is configured to substantially match the slope or slopes of the outer portion **620** of the window **615**, of other parts of the housing **600**, and/or of any other parts at the interface **800**.

[0113] Referring now to FIG. **8**A, in some embodiments the interface **800** includes an adapter **545**. In some embodiments, the adapter **545** facilitates coupling the device **500** to the housing **600**. In some embodiments, the device **500** complements the adapter **545**. In some embodiments, the inner perimeter **505** of the device **500** complements the adapter **545**. In some embodiments, the adapter **545** is substantially between the device **500** and the housing **600**. In some embodiments, the adapter is substantially between the device inner perimeter **505** and the moveable housing structure **605**. In some embodiments, the inner perimeter **505** adheres to, is fastened to, attaches to, or otherwise mechanically couples with the adapter **545**. In some embodiments the adapter **545** is a separate part from the device **500** and the housing **600**. For instance, the adapter **545** may couple with the inner perimeter **505** and the housing **600**, such as the moveable housing structure **605**. In some embodiments, the adapter **545** is integral with the device **500**. In some embodiments, the adapter **545** is integral with the housing **600**. In some embodiments, the interface **800** with the adapter **545** also includes the seal **535**. The seal **535** may be integral with the adapter **545**, with the device **500**, or with the housing **600**, or it may be a separate part that is not integral with any of the adapter **545**, the device **500**, or the housing **600**.

[0114] In some embodiments, the adapter **545** may have an elongated cross section such that it completely separates the device **500** from the housing **600**. In some embodiments, the adapter **545** is as wide as it is thick, or wider. In some embodiments, the adapter **545** may have different cross sectional shapes and/or areas at different sections. In some embodiments, the adapter **545** may not entirely separate the device **500** from the housing **600**. For instance, the adapter **545** may only separate a portion of the inner perimeter **505** from the

housing **600**, while another portion of the inner perimeter **505** butts directly against, or is otherwise mechanically coupled directly with, the housing **600**. In some embodiments, the inner perimeter **505** may have a stepped contour where the adapter **545** has a complementary stepped contour. In some embodiments, the adapter **545** may contact the bottom surface **520** and/or top surface **510** of the device **500**. For instance, the adapter **545** may have a U-shaped cross section that surrounds the inner perimeter **505**, the inner portion **525** or more of the top surface **510** and/or an inner portion or more of the bottom surface **520**. In some embodiments, the adapter **545** has an arcuate shape such that a cross section of the adapter **545** is swept around the housing for an angular amount defining a swept contour. In some embodiments, the angular amount is equal or similar to the angle of sweep **540**, which corresponds to the angle of sweep **540** of the device **500** (see FIG. **3**A). In some embodiments, the angular amount of sweep of the adapter **545** is less or more than the angle **540**. In some embodiments, the adapter **545** is continuous along the entire angular amount of sweep. In some embodiments the adapter **545** is discontinuous, such that in some locations along the sweep it has different cross sections. In some embodiments, the adapter **545** is comprised of multiple subparts located at various angular locations along the swept angular amount. Further, any features of the seal **535** as discussed above with respect to FIG. **4**A are applicable to the adapter **545**, and vice versa. For instance, the adapter **545** may likewise prevent, mitigate, or otherwise restrict the passage of fluid from the second flow domain **720** to the first flow domain **715**, etc.

[0115] As shown in FIG. **8**B, the interface **800** may include the device **500** and the housing **600**. In some embodiments, the device **500** complements the housing **600**. In some embodiments, the inner perimeter **505** of the device **500** complements the housing **600**. In some embodiments, the inner perimeter **505** adheres to, is fastened to, attaches to, or otherwise mechanically couples with the housing **600**. In some embodiments, the device **500** butts up against the housing **600**. In some embodiments, some portions of the device **500** butt up against the housing **600** and other portions of the device **500** are mechanically coupled to the housing **600**. Further, any features of the seal **535** as discussed above with respect to FIG. **4**A are applicable to the embodiments described with respect to FIG. **8**B, and vice versa. For instance, some embodiments of the interface **800** with the device **500** and the housing **600** may likewise prevent, mitigate, or otherwise restrict the passage of fluid from the second flow domain **720** to the first flow domain **715**, etc.

[0116] As shown in FIG. **8**C, the device may include a top surface continuation **512**. In some embodiments, the continuation **512** may be an extension of the top surface **510**, the bottom surface **520**, and/or the inner perimeter **505**. In some embodiments, the continuation **512** may continue over the window **615** and/or other parts or portions of the housing **600**. In some embodiments, the continuation **512** is transparent to electromagnetic energy. In some embodiments, the continuation **512** is glass. In some embodiments, the continuation **512** is the same or similar material as the window **615**. In some embodiments, the continuation **512** acts as the window **615** for the housing **600**. Thus, in some embodiments, the housing **600** without the device **500** may not have a window, and installing the device **500** with the continuation **512** to the housing **600** may provide the window **615**.

[0117] As shown, the device **500** with the continuation **512** may be coupled to the adapter **545**. In some embodiments, the adapter **545** is the seal **535**. In some embodiments, the adapter **545** may be between the inner perimeter **505** of the device **500** and the housing **600**. In some embodiments, the adapter **545** and or the device **500** may couple with the moveable structure **605**. In some embodiments, the interface **800** with the continuation **512** may contain no other parts, such that the device **500** and/or the continuation **512** directly contact the housing **600**. Further, any features of the seal **535** as discussed above with respect to FIG. **4**A are applicable to the embodiments described with respect to FIG. **8**C, and vice versa. For instance, some embodiments of the interface **800** with a continuation **512** may likewise prevent, mitigate, or otherwise restrict the passage of fluid from the second flow domain **720** to the first flow domain **715**, etc.

[0118] FIG. **8**D depicts an embodiment of the interface **800** where the window **615** extends to the perimeter of the housing **600**. In some embodiments, the window **615** may extend to the edge of the housing **600**. In some embodiments, the inner perimeter **505** of the device **500** may couple with the window **615** and/or other parts of the housing **600**. In some embodiments, the inner perimeter **505** of the device **500** may couple with the moveable structure **605**. In some embodiments where the window **615** extends to the perimeter of the housing **600**, the interface **800** may include the seal **535**, the adapter **545**, and/or any other parts. Further, any features of the seal **535** as discussed above with respect to FIG. **4** are applicable to the embodiments described with respect to FIG. **8**D, and vice versa. For instance, some embodiments of the interface **800** where the window **615** extends to the perimeter of the housing **600** may likewise prevent, mitigate, or otherwise restrict the passage of fluid from the second flow domain **720** to the first flow domain **715**, etc.

[0119] The various flows around the device **500** and the housing **600** may be described with respect to the density of the flow. As mentioned, a region of aero-optical flow **733** is a region of flow with reduced spatial and temporal density gradients in planes perpendicular to the housing axis **630**. The reduction in such density is with respect to flow around the housing **600** without the device **500**. The present disclosure allows for the flow fields around the housing **600**, and in particular over the window **615** and thus in the instrument's field of view **625**, to move closer to a flow field where the density does not vary at all in the aforementioned planes.

[0120] FIG. **9**A depicts a density field **900**, in the first flow domain **715** within the field of view **625** of a beam of electromagnetic energy along beam direction **905**, that is desirable. The flow is in a direction from left to right, as indicated by arrow **901**. The density field **900** is represented by isolines **910**. Along each isoline, the density of the fluid is the same. Thus, the density of the flow along isoline **911** is the same along that entire line, the density of the flow along isoline **912** is the same along that entire line, etc. As shown, the isolines **910** are perpendicular to the beam direction **905**, showing no spatial gradients across the wavefront. This helps prevent the wavefront of the beam from being distorted, as mentioned above.

[0121] FIG. **9**B depicts the resulting density field **900** shown by normalized isolines **910** from a simulation of flow over the housing **600** without the device **500**. The flow is in a direction from left to right, as indicated by arrow **901**. The isolines **910** are on a plane that is perpendicular to the window **615**. As shown, the isolines **910** are severely skewed and

non-planar, showing high spatial gradients across the wavefront. The gradients are a consequence of the separated flow over the window **615** and a shear layer in the beam path. The isolines **910** further fluctuate temporally as the flow is separated over the window **615**.

[0122] FIG. **9**C depicts the resulting density field **900** shown by normalized isolines **910** from a simulation of flow over the housing **600** with the device **500**. The flow is in a direction from left to right, as indicated by arrow **901**. The isolines **910** are on a plane that is perpendicular to the window **615**. As shown in FIG. **9**C, the isolines **910** in the density field **900** are much closer to the isolines **910** of desired density field **900** in FIG. **9**A than are the isolines **910** in the density field **900** without the device **500** as shown in FIG. **9**B. This is especially true over the field of view **625** of the optical instrument. The improved density field **900** in FIG. **9**C is due in part to the device **500** maintaining attached flow over the window **615** and the field of view **625**. The isolines **910** further do not fluctuate or show substantially reduced fluctuation temporally because the flow is not separated over the window **615**.

[0123] The various configurations for the systems and devices described above may be used in a variety of manners. FIG. **10** depicts an embodiment of a method **1000** for controlling fluid flow over the window **615** of the optical instrument housing **600** on the vehicle **400** in a freestream flow field **700**. The method **1000** may include step **1010** wherein the device **500** is coupled to the housing **600**. In step **1010**, the device **500** may be fastened, adhered, bonded, attached, connected, tied, or otherwise mechanically coupled to the housing **600**. In some embodiments, step **1010** includes coupling the device **500** to the housing **600** to produce any of the configurations of the interface **800** described above. For example, the device **500** may be coupled to the housing **600** where the interface **800** includes the seal **535**, the adapter **545**, the continuation **512**, and/or any other parts necessary to mechanically couple the various items. Further, step **1010** includes coupling the device **500** to the housing **600** and/or to any other parts, including the seal **535**, the adapter **545**, the continuation **512**, and/or any other parts necessary to mechanically couple the various items together.

[0124] The method **1000** may then proceed to step **1020** where the slope of a surface of the device **500** matches the slope of a surface of the housing **600**. This may include matching the slope of any surfaces of the device **500** with any surfaces of the housing **600**, as well as any other surfaces present in the interface **800**. For example, step **1020** may include matching the slopes of the inner portion **525** of the top surface **510** of the device **500**, the edge of the seal **535**, the edge of the moveable housing structure **605**, and/or the outer portion **620** of the window **615**.

[0125] The method **1000** may then proceed to step **1030** where a contiguous surface is formed with the device **500** and the housing **600**. This may include forming a contiguous surface with any surfaces of the device **500** and any surfaces of the housing **600**, as well as any other surfaces present in the interface **800**. For example, step **1030** may include forming a contiguous surface with the inner portion **525** of the top surface **510** of the device **500**, the edge of the seal **535**, the edge of the moveable housing structure **605**, and/or the outer portion **620** of the window **615**.

[0126] Next, the method **1000** may proceed to step **1040** wherein the freestream flow field **700** is split into two flow domains. This may include, for example, splitting the freestream flow field **700** with the device **500** into the first flow domain **715** and the second flow domain **720**. This may also include splitting the upstream flow field **705** with the device **500** into the first flow domain **715** and the second flow domain **720**.

[0127] The method **1000** may then proceed to step **1050** wherein an aero-optical flow region **733** is induced from the freestream flow field **700**. This may include, for example, inducing the region **733** in the first flow domain **715**. Step **1050** may further include maintaining the aero-optical flow region **733** over a range of angular orientations of the device **500** relative to the direction of the freestream flow field **700**.

[0128] Although this invention has been disclosed in the context of certain embodiments and examples, it will be understood by those skilled in the art that the present invention extends beyond the specifically disclosed embodiments to other alternative embodiments and/or uses of the invention and apparent modifications and equivalents thereof. In addition, while a number of variations of the invention have been shown and described in detail, other modifications, which are within the scope of this invention, will be readily apparent to those of skill in the art based upon this disclosure. It is also contemplated that various combinations or sub-combinations of the specific features and aspects of the embodiments may be made and still fall within the scope of the invention. Accordingly, it should be understood that various features and aspects of the disclosed embodiments can be combined with or substituted for one another in order to form varying modes of the disclosed invention. Thus, it is intended that the scope of the present invention herein disclosed should not be limited by the particular disclosed embodiments described above, but should be determined only by a fair reading of the claims that follow.

What is claimed is:

1. An apparatus for controlling fluid flow over a window of a moveable optical instrument housing, the housing comprising a perimeter and at least partially protruding from a vehicle into a freestream flow field, the apparatus comprising:

an inner perimeter configured to complement the perimeter of the housing;

an arcuate top surface comprising a curvature and configured to extend into an upstream portion of the freestream flow field; and

an arcuate outer perimeter coupled to the arcuate top surface,

wherein the apparatus is configured to couple with the housing and to split the freestream flow field into a first flow field that is at least partially above the apparatus and window and a second flow field that is at least partially under the apparatus and around the housing;

wherein the first flow field comprises an aero-optical flow region that extends at least partially over the arcuate top surface and continues at least partially over the window, and

wherein the aero-optical flow region is maintained within a range of angular orientations of the apparatus relative to the freestream flow.

2. The apparatus of claim **1**, further comprising:

an inner portion of the arcuate top surface configured to be substantially flush with an outer portion of the window when the apparatus is coupled with the housing.

3. The apparatus of claim **1**, further comprising:

an inner portion of the arcuate top surface configured to be substantially contiguous with an outer portion of the window when the apparatus is coupled with the housing.

4. The apparatus of claim **3**, wherein a slope of the inner portion of the arcuate top surface is configured to substantially match a slope of the outer portion of the window, wherein the outer portion of the window is adjacent to the inner portion of the arcuate top surface.

5. The apparatus of claim **1**, further comprising:

an inner portion of the arcuate top surface,

wherein the apparatus is configured such that a boundary layer in the first flow field over the inner portion comprises a velocity profile substantially similar to a downstream velocity profile of the boundary layer over an outer portion of the window, and

wherein the outer portion of the window is adjacent to the inner portion of the arcuate top surface.

6. The apparatus of claim **1**, wherein the inner perimeter is substantially impermeable to the freestream flow field, the first flow field and the second flow field.

7. The apparatus of claim **1**, wherein the inner perimeter further comprises:

a seal,

wherein the seal is substantially impermeable to the freestream flow field, the first flow field and the second flow field.

8. The apparatus of claim **1**, wherein the arcuate outer perimeter is rounded.

9. The apparatus of claim **1**, wherein the arcuate outer perimeter comprises a radius.

10. The apparatus of claim **1**, wherein the arcuate top surface and the outer perimeter form a substantially smooth surface.

11. The apparatus of claim **1**, wherein the curvature curves toward the second flow field.

12. The apparatus of claim **1**, further comprising:

a bottom surface, wherein the bottom surface and the arcuate top surface define a thickness therein.

13. The apparatus of claim **12**, wherein the thickness is substantially uniform.

14. The apparatus of claim **12**, wherein the thickness is substantially nonuniform.

15. The apparatus of claim **1**, wherein the inner perimeter, the arcuate top surface, the outer perimeter and the bottom surface form a plurality of cross sections of the apparatus.

16. The apparatus of claim **15**, wherein at least one of the cross sections is configured to arcuately extend at least partially around the perimeter of the window, and wherein at least one of the cross sections is configured to extend at least partially toward the freestream flow field.

17. The apparatus of claim **15**, wherein at least one of the cross sections is in a plane such that at least part of the freestream flow field in the plane is perpendicular to a line that is tangent to a point on an edge of the cross section.

18. The apparatus of claim **15**, wherein at least one of the cross sections is configured to extend at least 180 degrees around the perimeter of the window.

19. The apparatus of claim **1**, wherein the optical instrument housing is moveable in at least two dimensions.

20. The apparatus of claim **19**, wherein the housing is rotatable about a pitch axis and a yaw axis.

21. The apparatus of claim **20**, wherein the aero-optical flow region is maintained for rotations about the pitch and yaw axes of at least +/−135 degrees.

22. The apparatus of claim **1**, wherein a Strehl ratio in the aero-optical flow region is at least 0.7 for electromagnetic radiation consisting of a wavelength of about 1 micrometer.

23. The apparatus of claim **1**, wherein the optical instrument housing is substantially spherical and the window is substantially planar.

24. The apparatus of claim **23**, wherein the optical instrument housing comprises a turret housing on the vehicle, wherein the vehicle is an aircraft.

25. The apparatus of claim **24**, wherein the apparatus is coupled to the turret housing.

26. A method for controlling fluid flow over the window of an optical instrument housing on a vehicle in a freestream flow field, the method comprising:

splitting an upstream portion of the freestream flow field into a first flow field comprising an aero-optical flow region and a second flow field using an apparatus comprising:

an inner perimeter configured to complement a perimeter of the housing,

an arcuate top surface comprising a curvature and configured to extend into the upstream portion of the freestream flow field, and

an arcuate outer perimeter coupled to the arcuate top surface,

wherein the apparatus is configured to couple with the housing;

wherein the aero-optical flow region extends at least partially over the top surface and continues at least partially over the window, and

wherein the aero-optical flow region is maintained over a range of angular orientations of the apparatus relative to the freestream flow.

27. The method of claim **26**, further comprising:

coupling the apparatus to the housing.

28. The method of claim **27**, further comprising:

forming a substantially contiguous surface with an inner portion of the top surface and the perimeter of the housing.

29. The method of claim **27**, further comprising:

matching the slope of an outer portion of the housing with the inner portion of the top surface, wherein the outer portion of the housing is adjacent to the inner portion of the top surface.

30. A system for controlling fluid flow over a window of a moveable optical instrument housing that protrudes from a vehicle into a freestream flow field, the system comprising:

a housing defining an axis; and

an arcuate lip comprising a curved top surface and outwardly extending away from the axis,

wherein the lip is configured to split the freestream flow field into a first flow field above the lip and window and a second flow field under the lip and around the housing,

wherein the first flow field comprises an aero-optical flow region that extends at least partially over the top surface of the lip and continues at least partially over the window, and

wherein the aero-optical flow region is maintained over a range of angular orientations of the axis relative to the freestream flow.

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